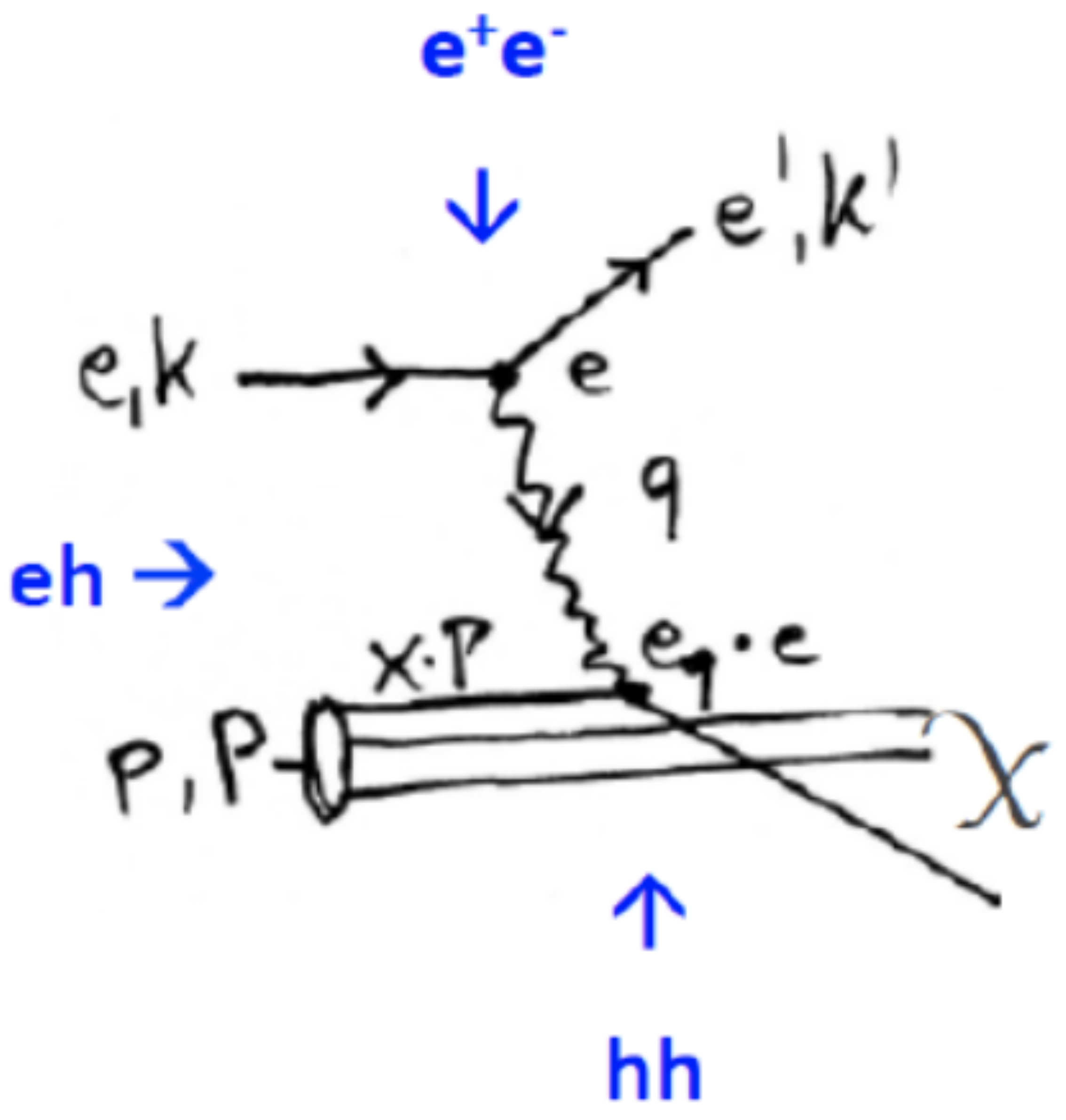
Energy Frontier Workshop - Open Questions and New Ideas
July 20th 2020

Future (energy frontier) Electro-Proton and Electron-Hadron Colliders



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for the LHeC/FCC-eh Study Group

Contents:

1. Introduction.

2. Physics:
   ➜ QCD: PDFs, impact at small x, α_s;
   ➜ eA;
   ➜ EW: impact on the LHC;
   ➜ Top: V_{tb}, FCNC;
   ➜ Higgs: bb, cc, LHeC and HL-LHC combinations;
   ➜ BSM: new scalars from Higgs, SUSY, heavy neutrinos, dark photons.

3. Summary and Open questions.

References:

- *Future Circular Collider CDR: Vol. 1 Physics opportunities (Eur. Phys. J. C79 (2019) no.6, 474) and Vol. 3 FCC-hh: The Hadron Collider (Eur. Phys. J. ST 228 (2019) no.4, 755-1107);*
- *LHeC CDR, 1206.2913;*
- *2019 LHeC and FCC-eh workshop, https://indico.cern.ch/event/835947/;*
- *LHeC/FCC-eh talks at DIS 2019, https://indico.cern.ch/event/749003/ and FCC Week 2019, https://indico.cern.ch/event/727555/;*
- *European Strategy Update: Briefing Book, 1910.11775;*
- *Update of the 2012 LHeC CDR to appear this month.*

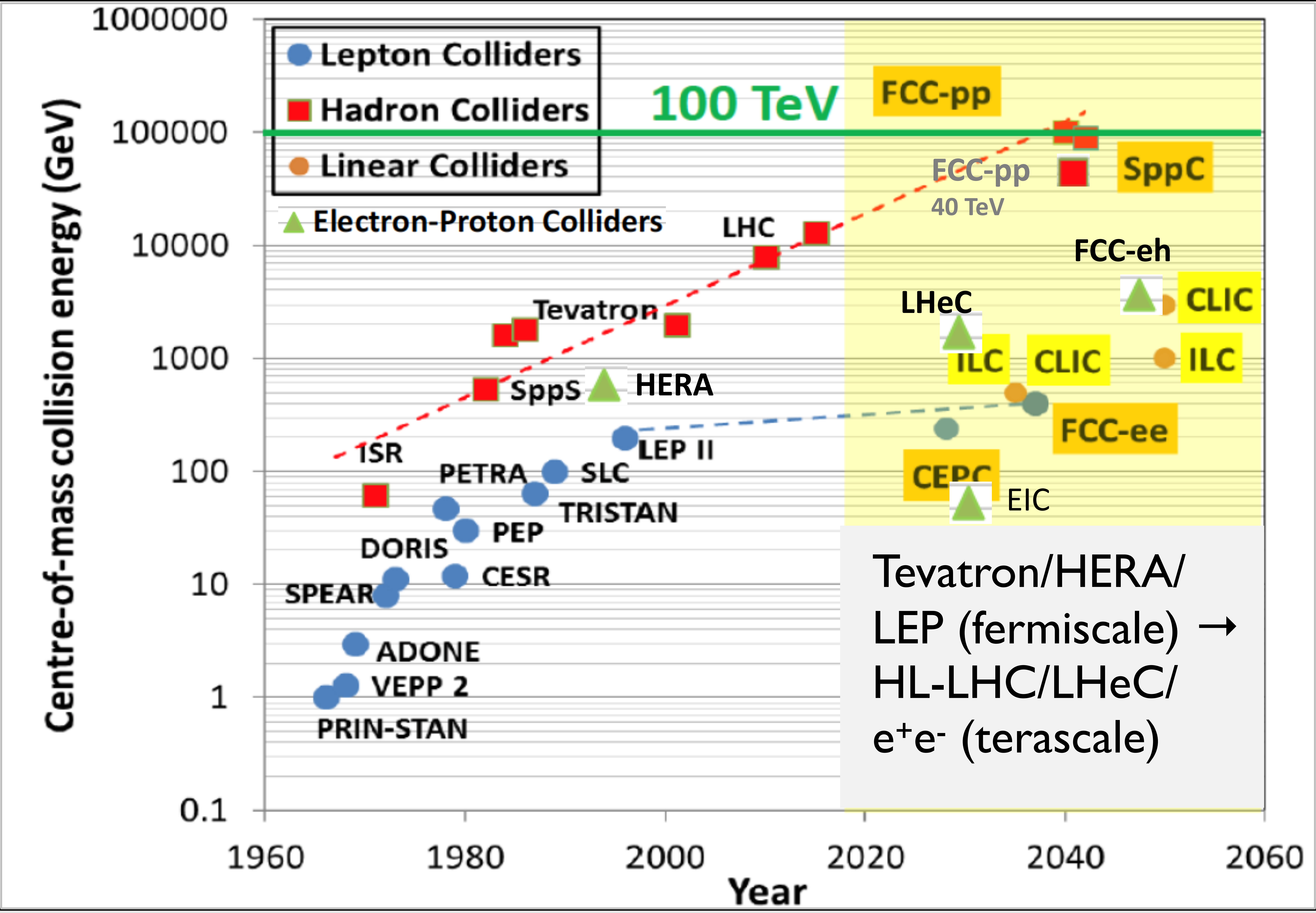
See the talks by Oliver Brüning (AF-EF, Jun-24), Daniel Britzger (EF5-EF6, Jun-30), Max Klein (AF4, Jul-8) and Fred Olness (Preparatory Meeting, Jul-7).

http://lhec.web.cern.ch/

Accelerators:

• LHeC idea born in 2005: upgrade of the HL-LHC to study DIS at the terascale.

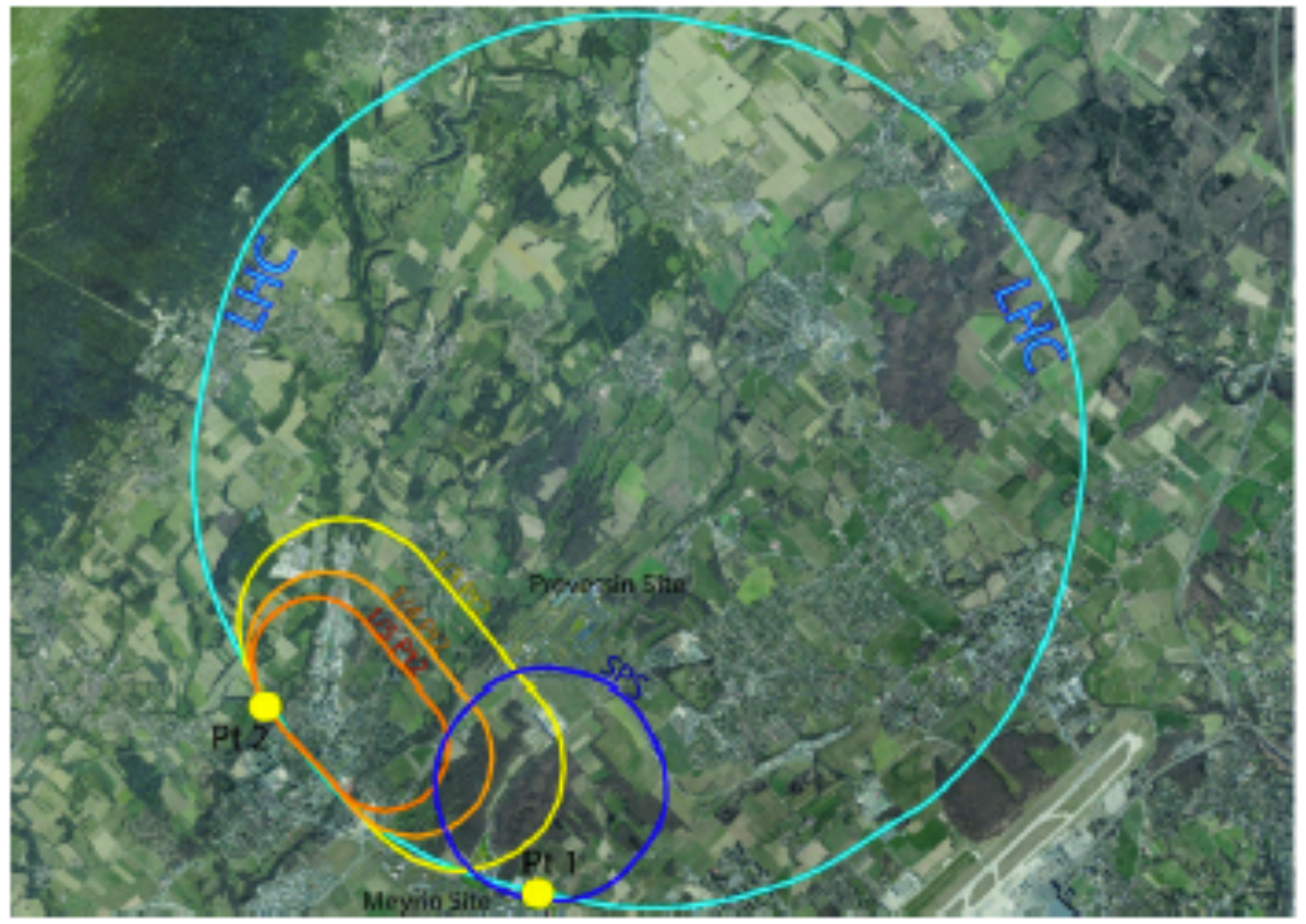
• **It must be able to run concurrently with pp** (also FCC-eh), plus limitations on power consumption, high luminosity for Higgs studies,… ⇒ energy recovery linac as baseline.



Tevatron/HERA/LEP (fermiscale) → HL-LHC/LHeC/e^+e^- (terascale)

Accelerators:

M Klein, O Bruening on LoIs for future ep:
Snowmass Meeting on TeV Colliders
8 July 2020, for the LHeC+PERLE+FCCeh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

CERN-ACC-Note-2020-0002 →arXiv (July)

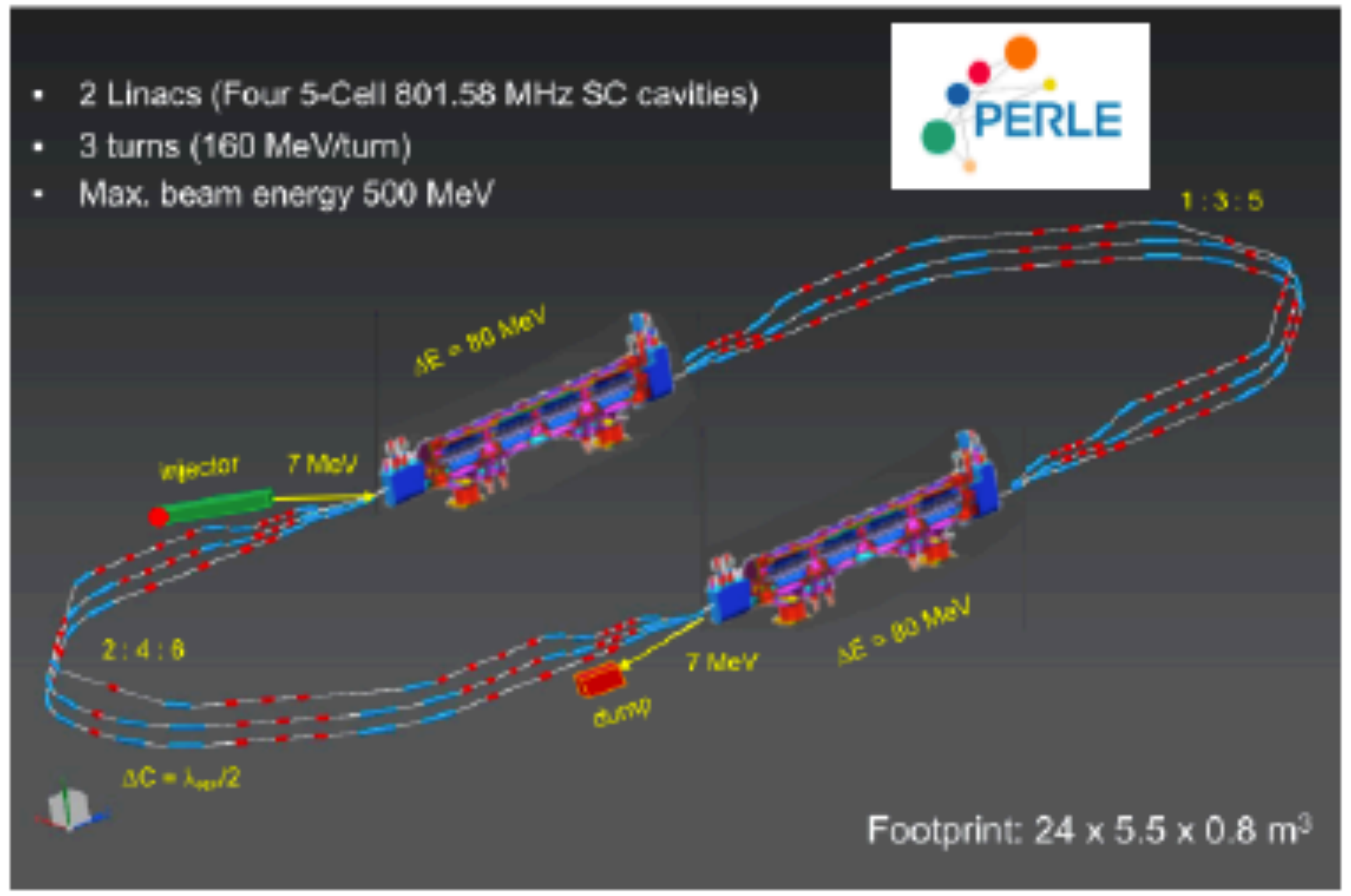
LHeC, PERLE and FCC-eh

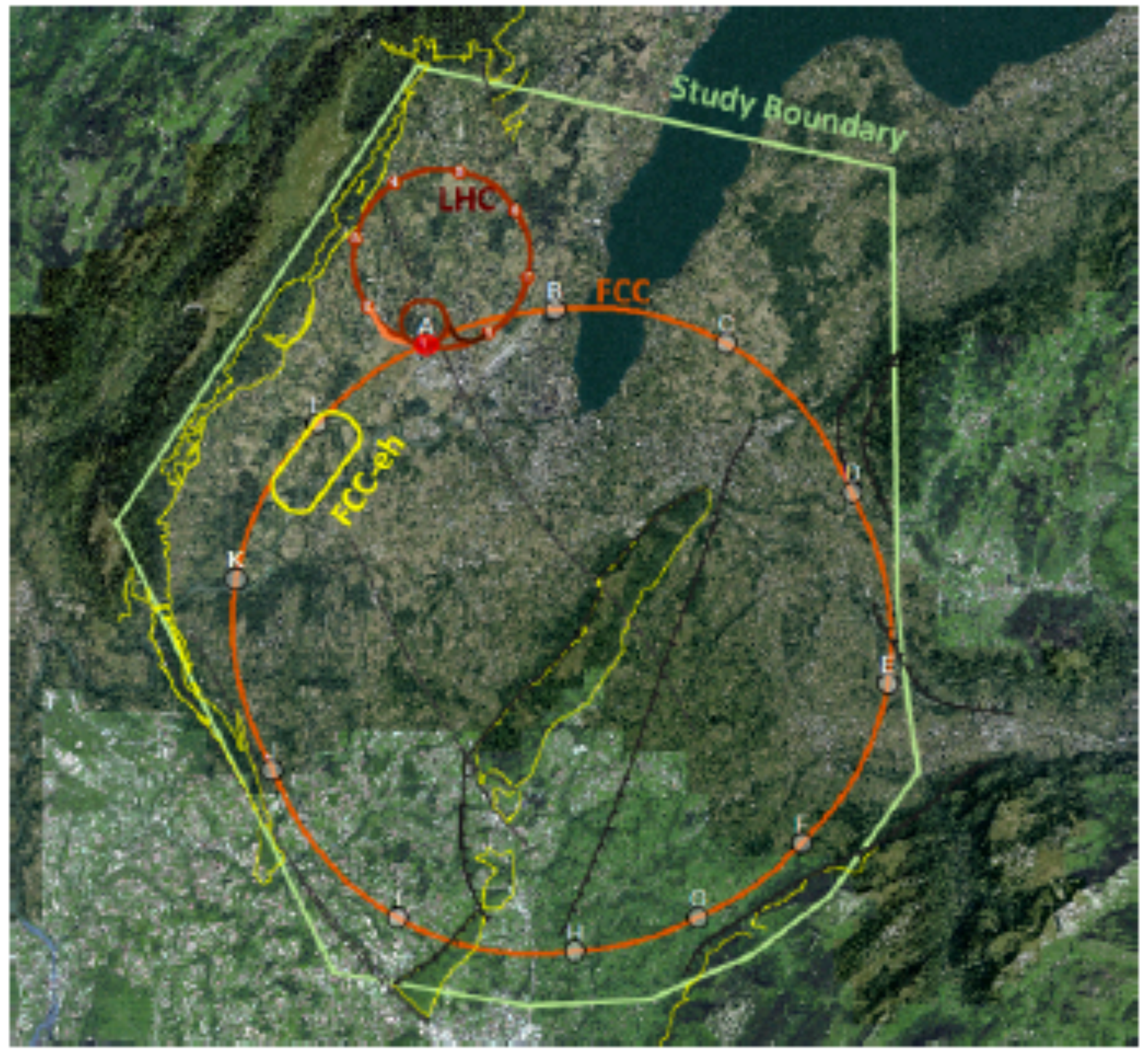
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration
I_e=20mA, 802 MHz SRF, 3 turns →
E_e=500 MeV → first 10 MW ERL facility

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (IJC), +





60 x 50000 GeV^2: 3.5 TeV ep collider

Operation: 2050+, Cost (of ep) O(1-2) BCHF

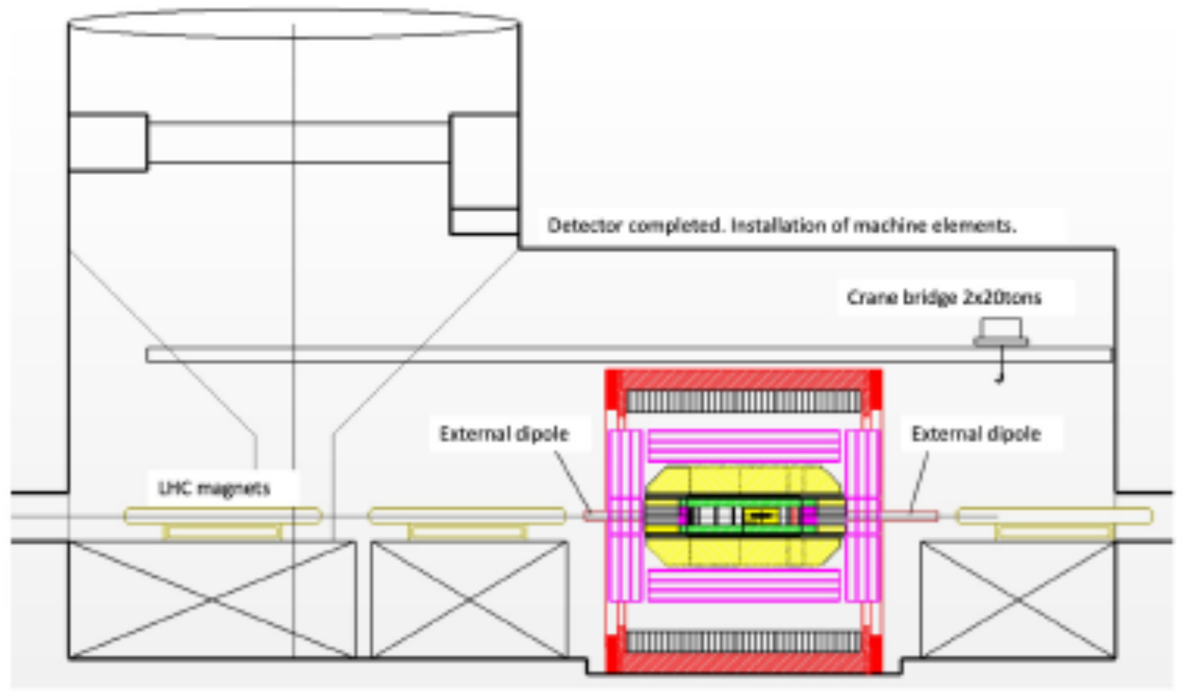
Concurrent Operation with FCC-hh

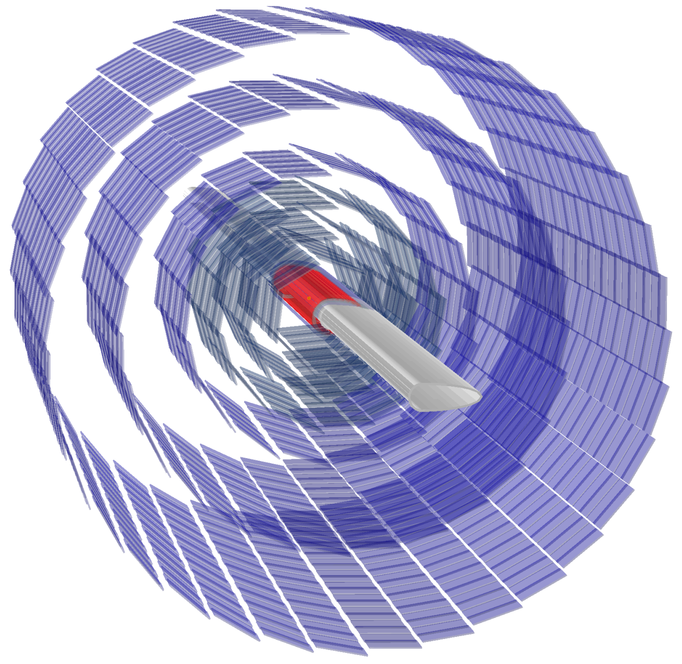
FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

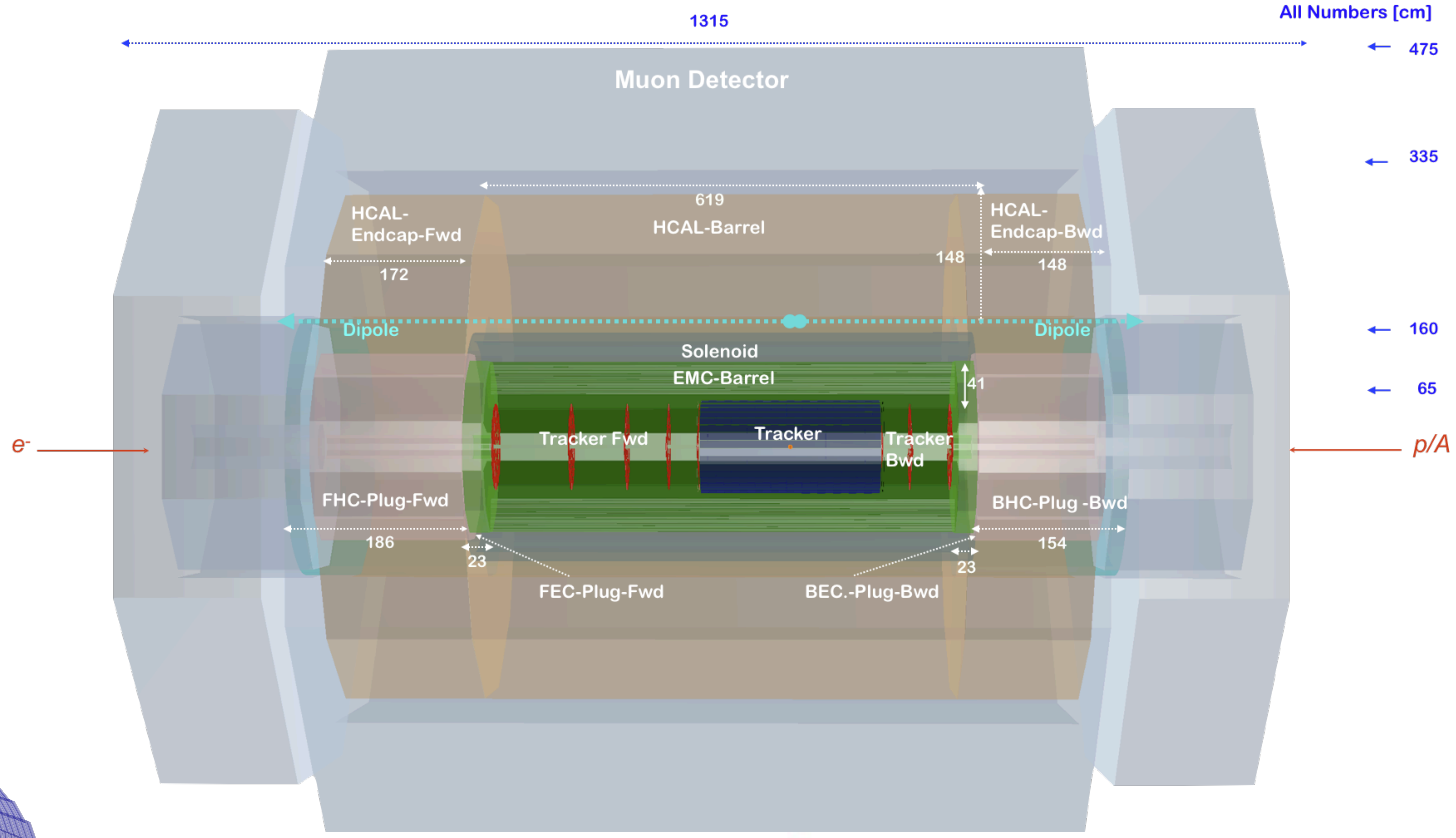
Detector: LHeC

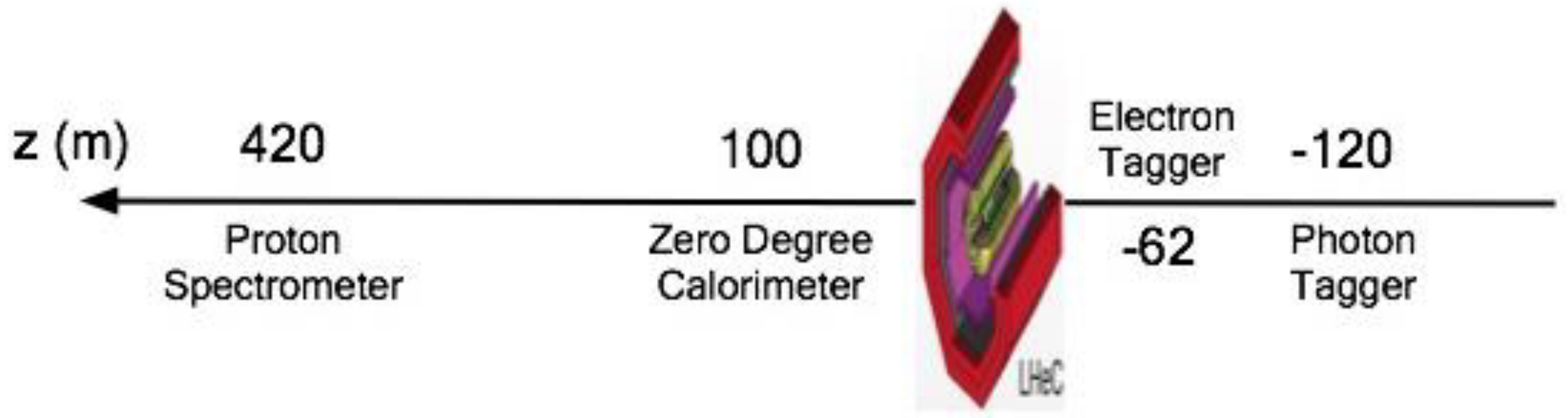
- 1 degree acceptance ($|\eta|<4.7$) required for small x and H.
- Central detector: increased tracker radius wrt CDR, radiation level 1/1000 wrt LHC → ideal for CMOS etc.
- Forward/backward detectors: e-, γ-taggers, ZDC, p-spectrometer (FP420).
- Installation in IP2, keeping L3 magnet, feasible in two years.
- FCC: larger tracking, two solenoids?



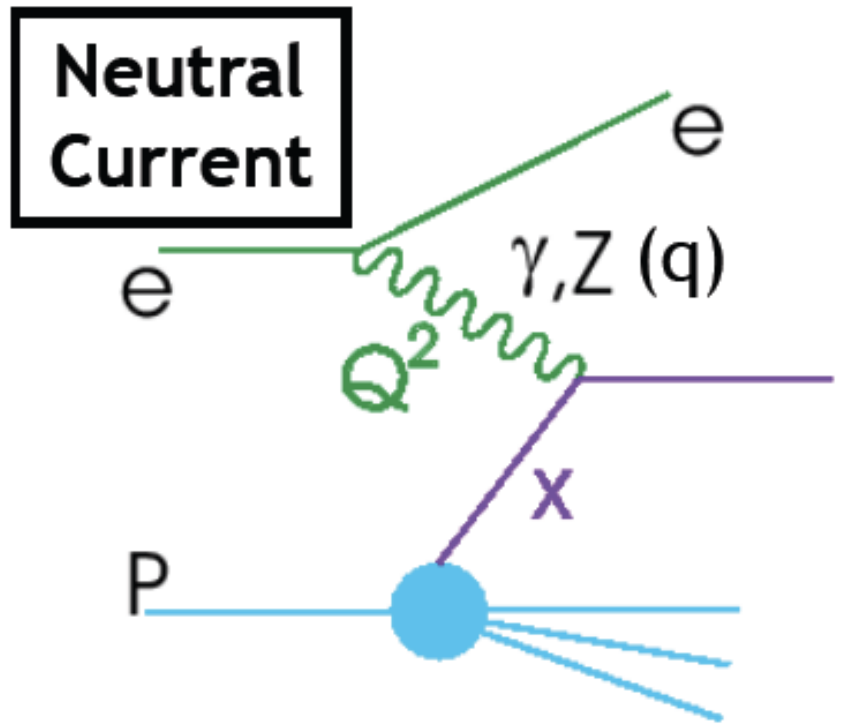


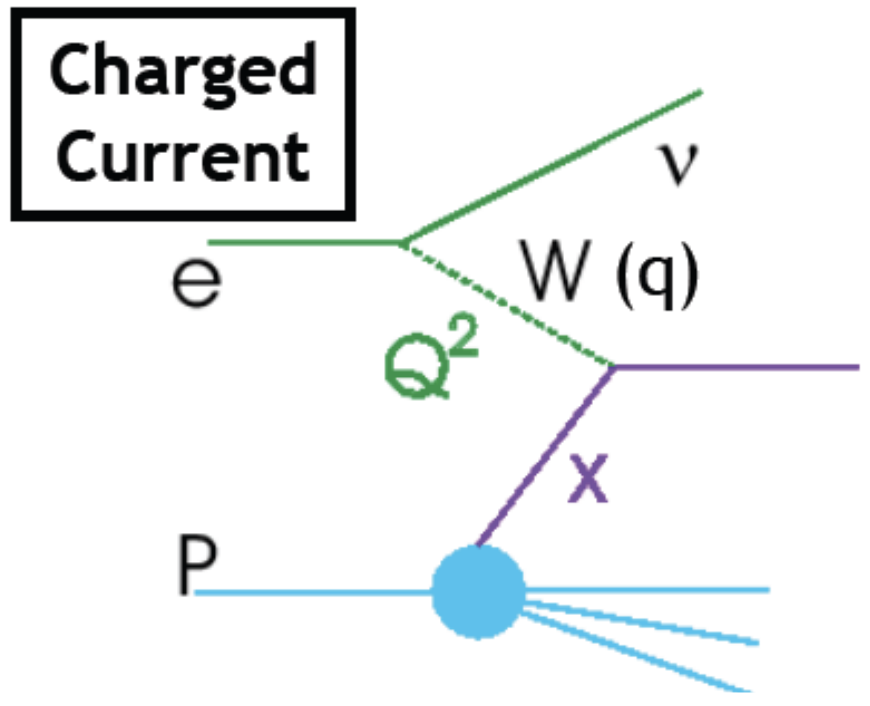
LHeC (FCC-eh): R=4.6 (6.2) m, L=13.6 (19.3) m

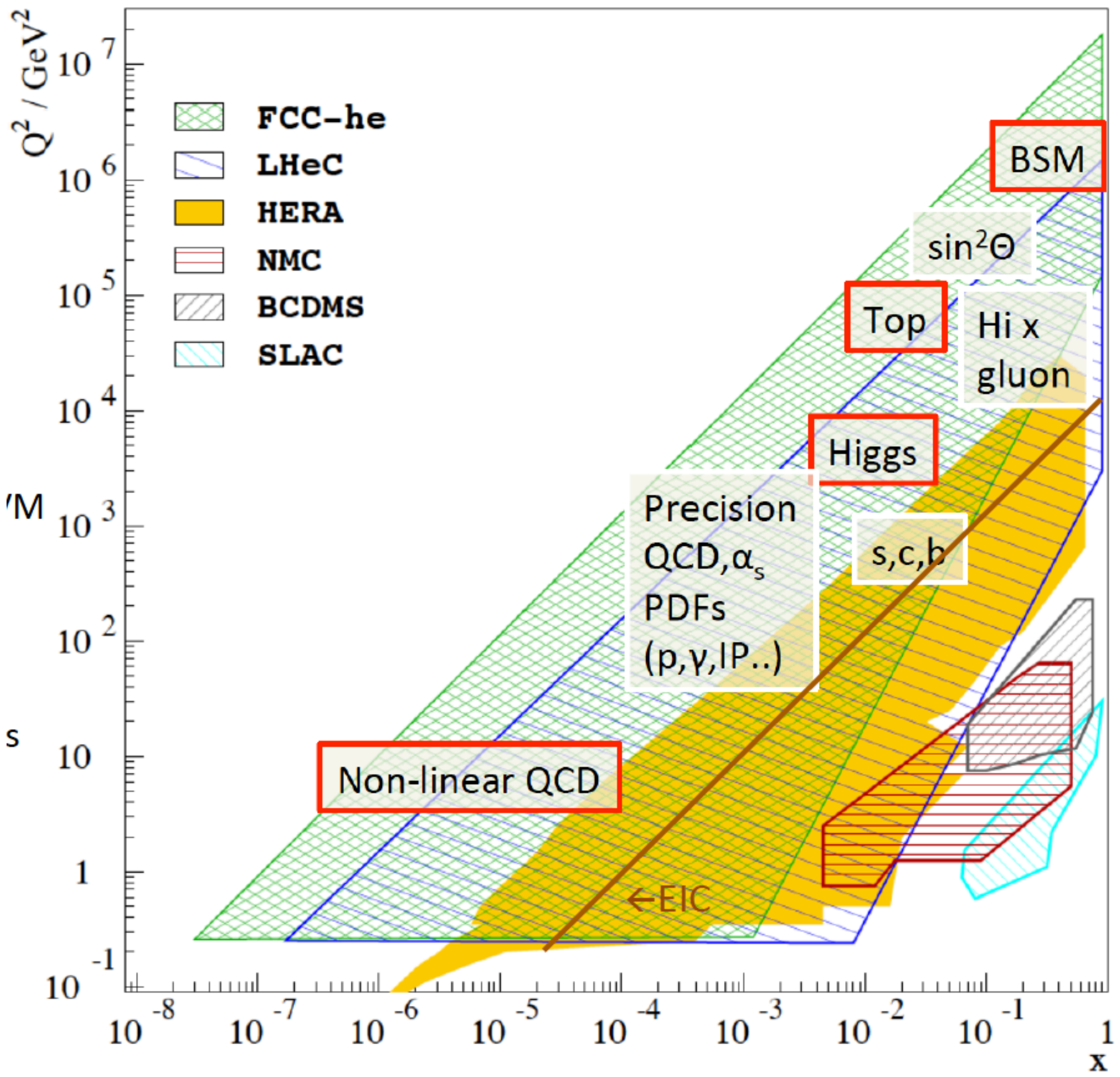




Summary of physics:







- ep/eA colliders are the cleanest High Resolution Microscope:
  ➜ Precision and discovery in QCD;
  ➜ Study of EW / VBF production, LQ, multi-jet final states, forward objects,…

- Empower the LHC Search Programme (e.g. PDF, EW measurements).

- Transform the LHC into a high precision Higgs facility.

- Has unique and complementary discovery potential of BSM particles (prompt and long-lived).

- **Overall: a unique Particle and Nuclear Physics Facility.**

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   - ➜ BSM: new scalars from Higgs, SUSY, heavy neutrinos, dark photons.

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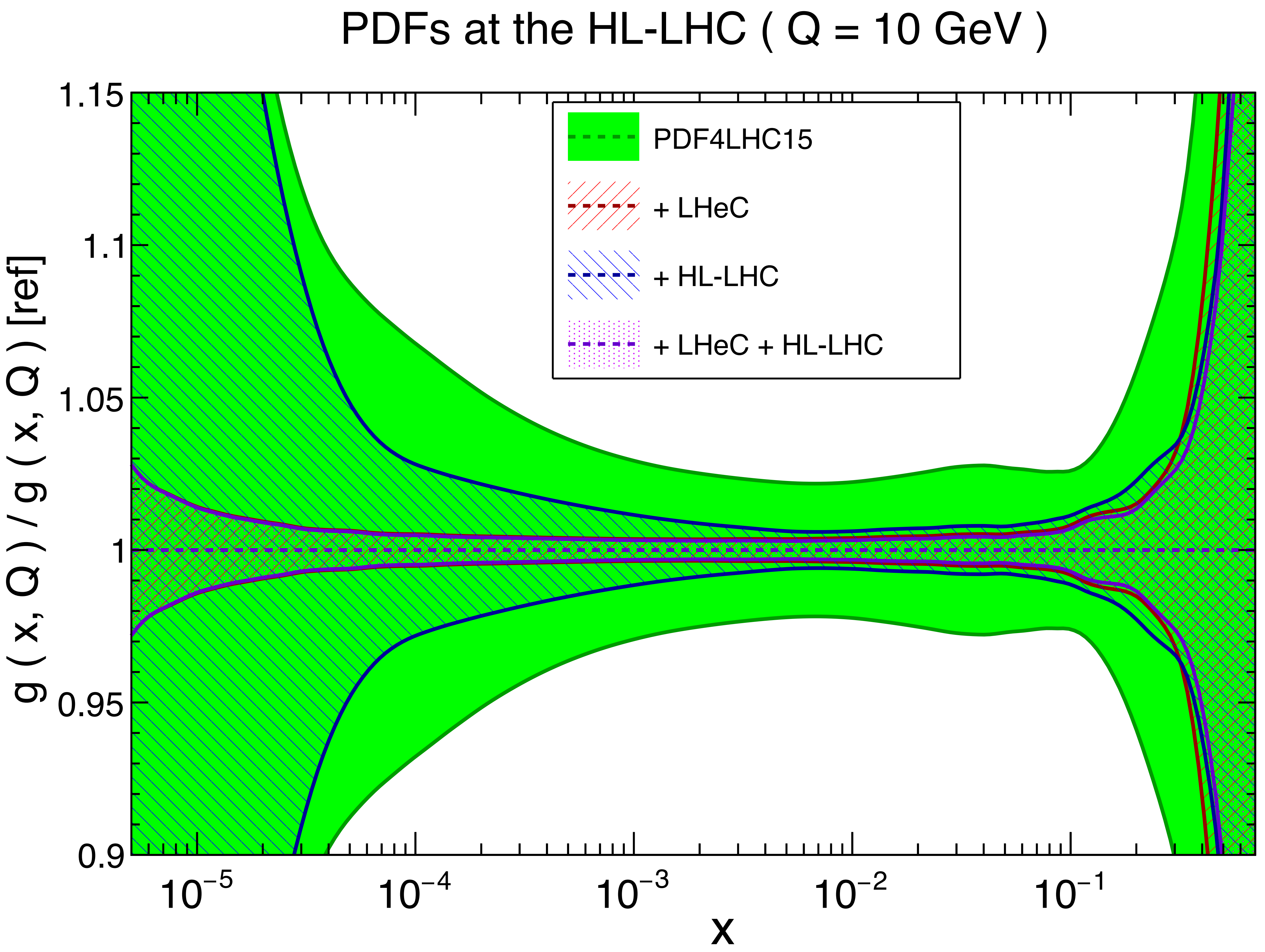
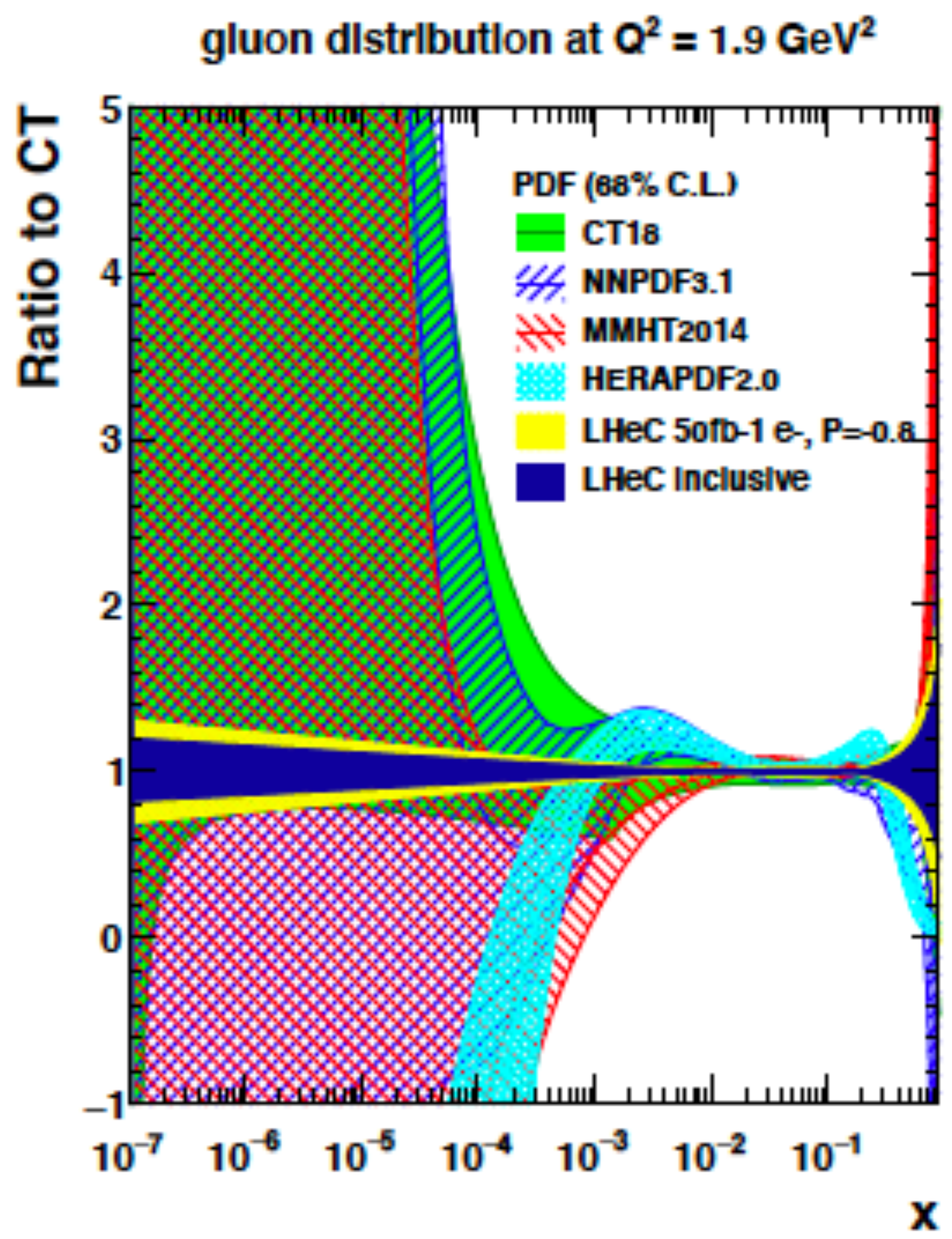
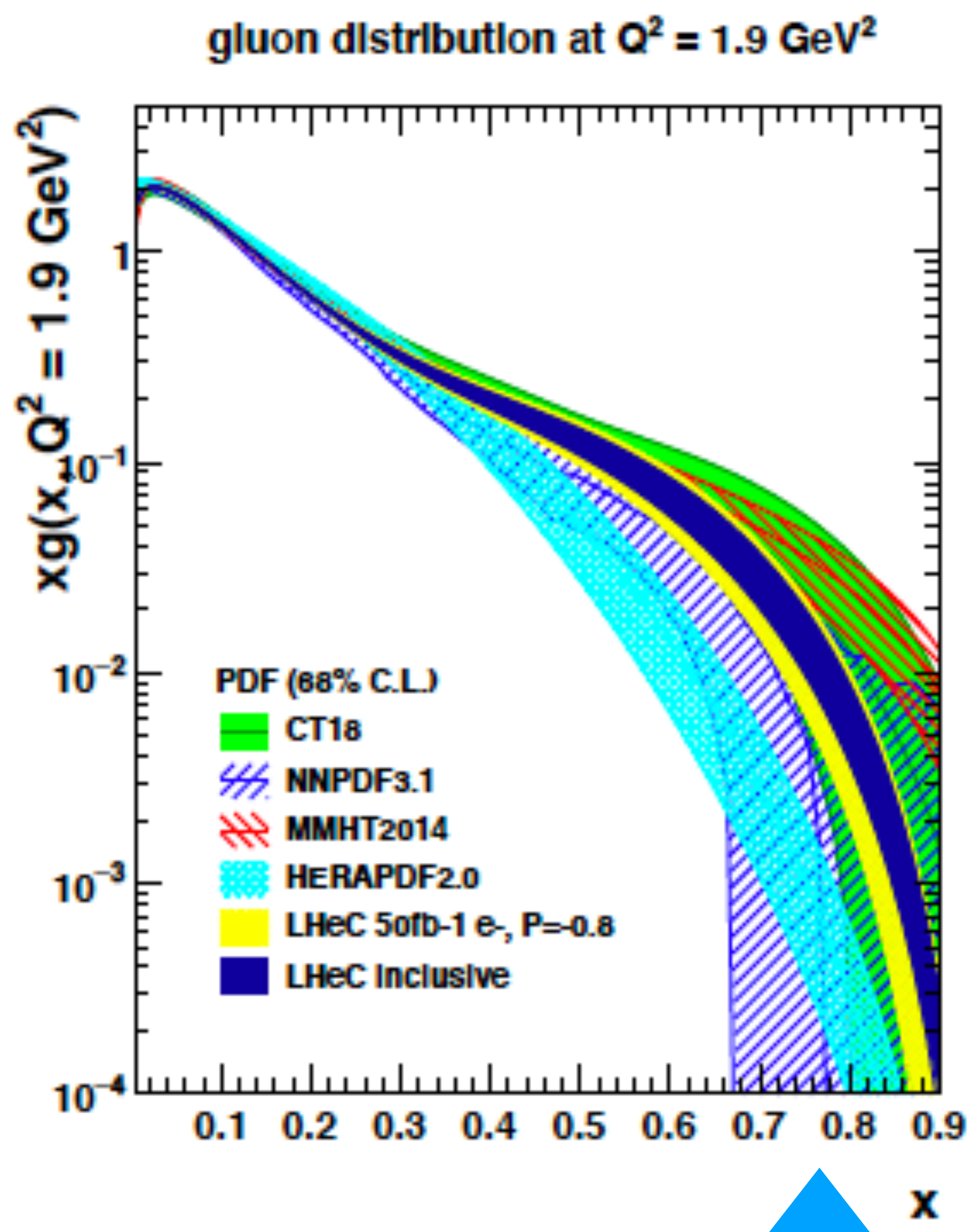
QCD: parton densities

- For the 1st time, complete resolution of flavour and gluon parton substructure in single system/ experiment, in unprecedented kinematic range (no higher twists or nuclear corrections,…).



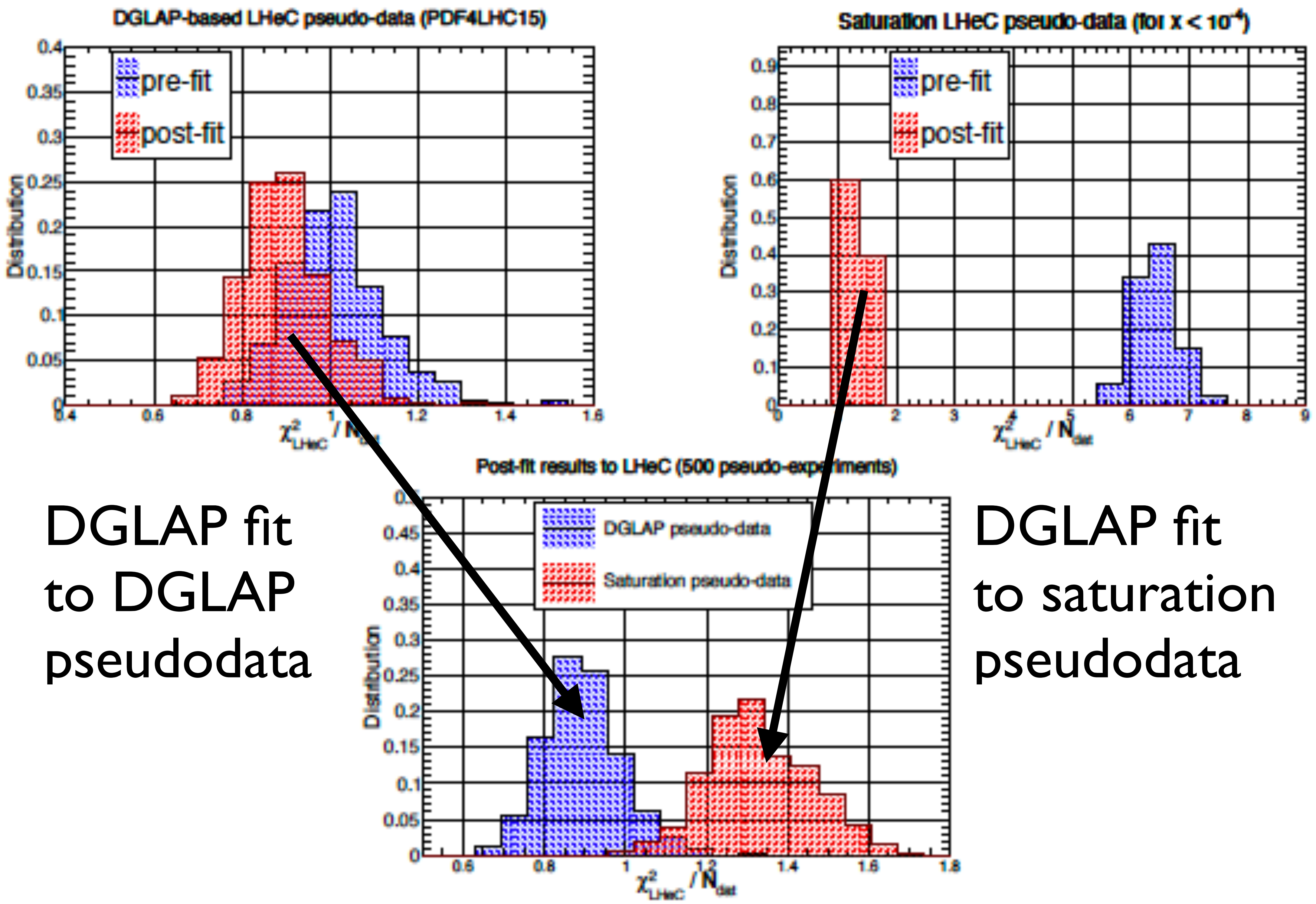




- PDFs and α_s crucial for HL-LHC: high precision electro-weak, Higgs measurements (e.g. remove essential part of QCD uncertainties of gg→H), extension of high mass search range, non-linear low x parton evolution: saturation.

QCD: small x and α_s

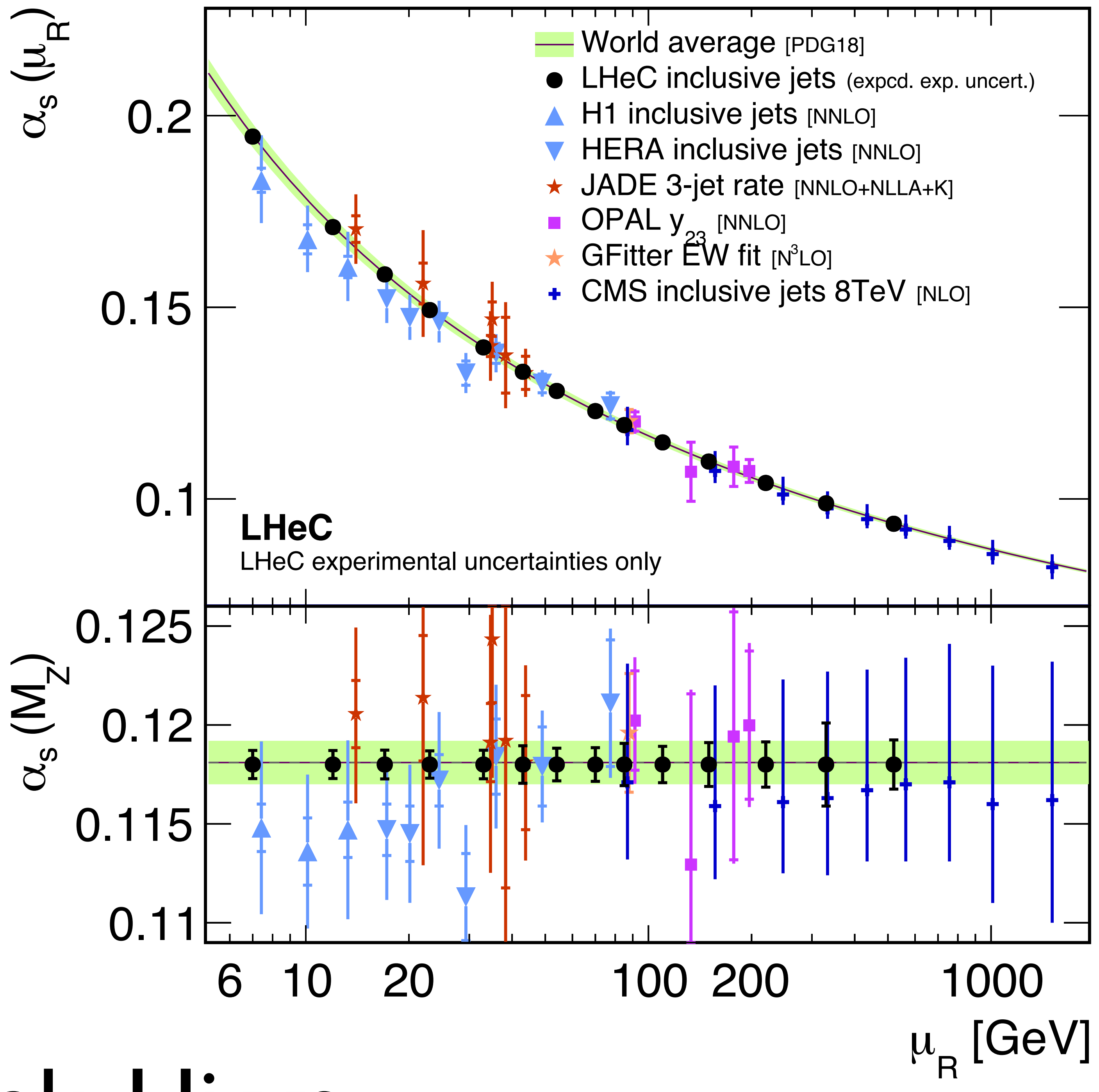
- **Breaking of *standard* factorisation**: new non-linear regime of QCD, implications for FCC (e.g. gg→H).



- **α_s to per mille accuracy (incl.+jets):**

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$



- **PDFs and α_s crucial for HL-LHC**: high precision electro-weak, Higgs measurements (e.g. remove essential part of QCD uncertainties of gg→H), extension of high mass search range, non-linear low x parton evolution: saturation.

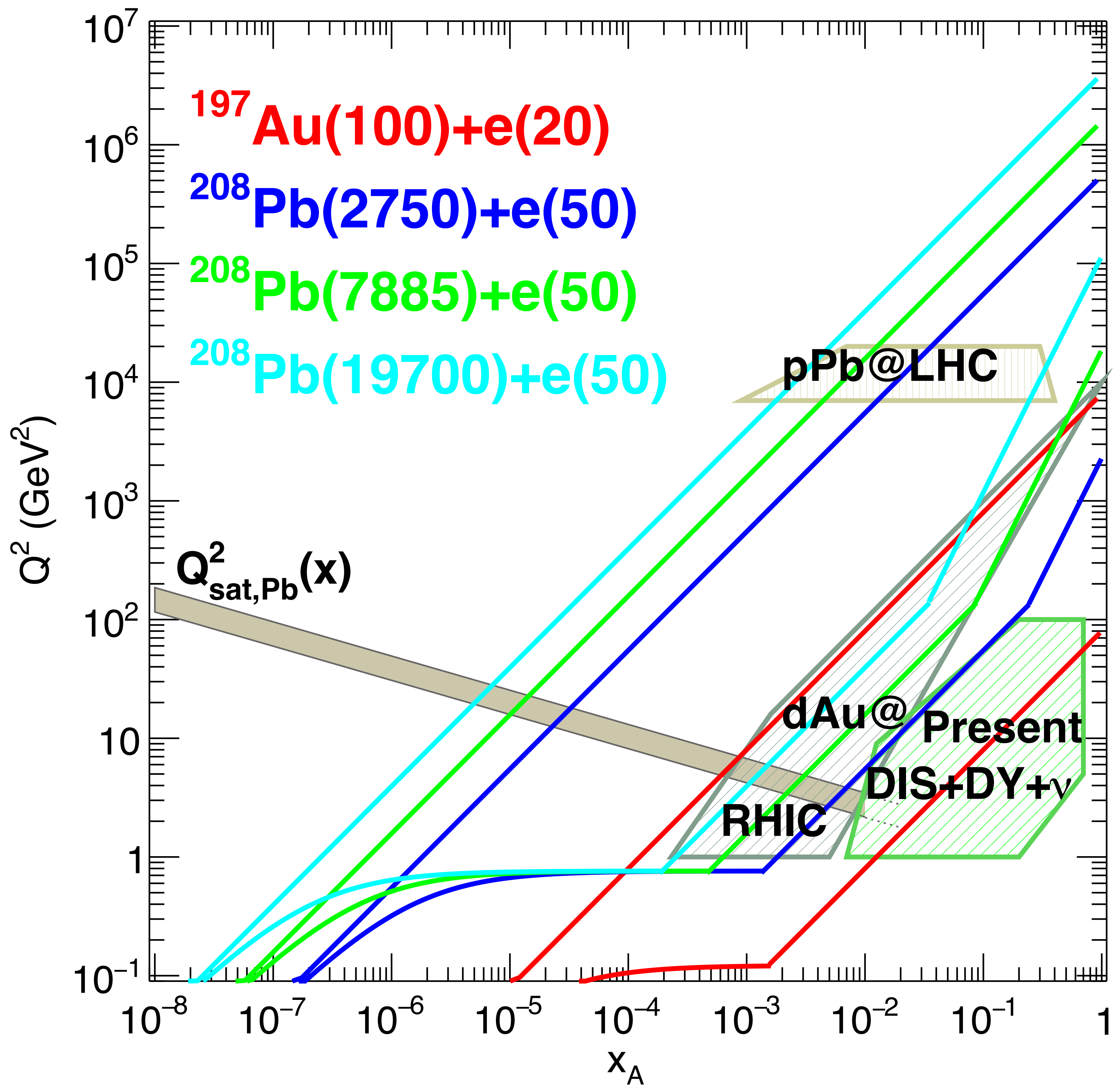
eA:

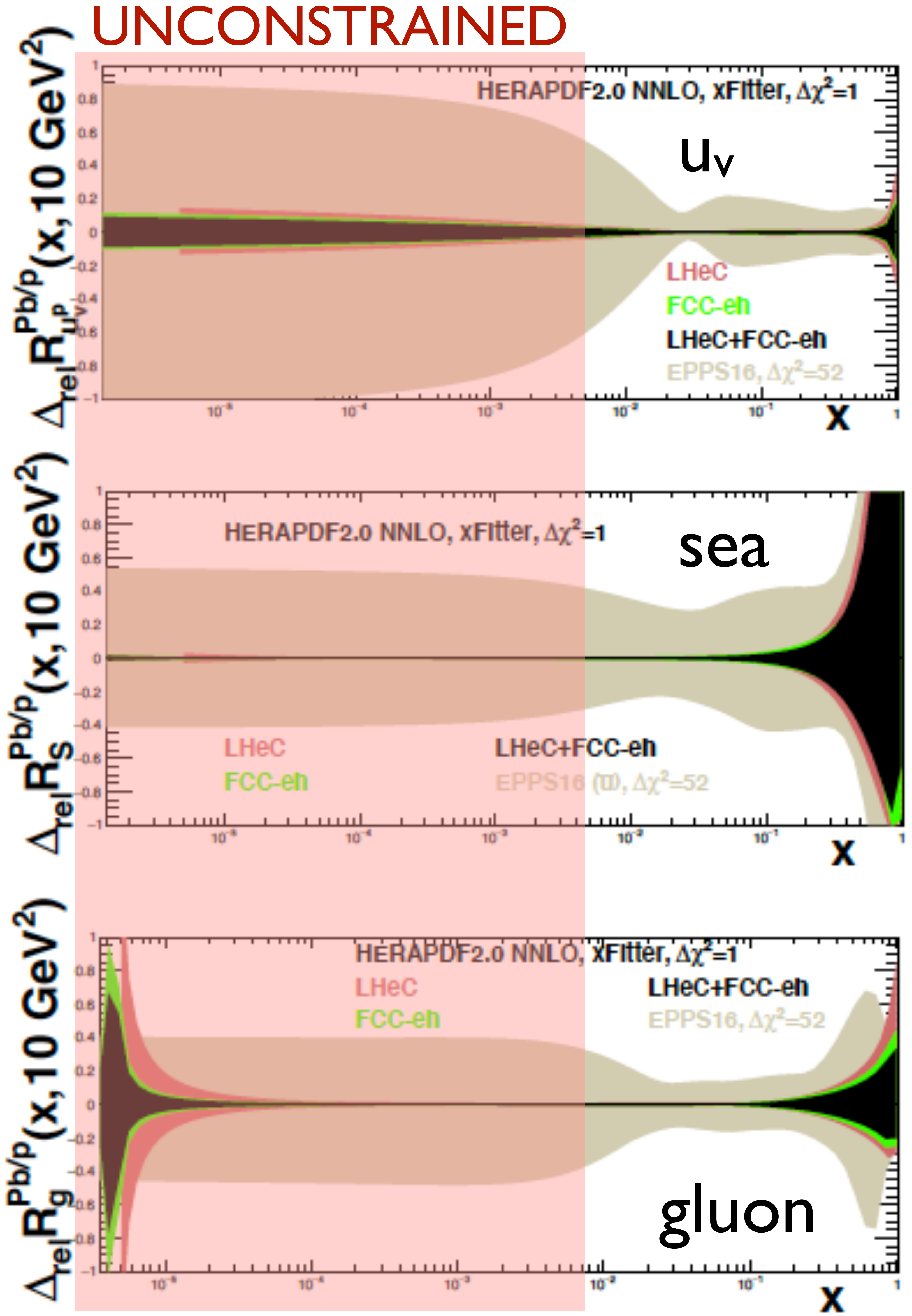
- eA collisions at LHeC/FCC-eh: region presently explored in DIS extended by ~4 decades down in x and up in Q^2.

- Determination of inclusive and diffractive nuclear parton densities for a single nucleus, with flavour unfolding.
- Studies of transverse structure.
- Saturation (ep & eA, nuclear enhancement).
- Flavour dependent anti shadowing, Gribov relation with diffraction,…

with strong implications on the pA/AA programmes at the HL-LHC and FCC-hh.

Luminosity (per nucleon)=10^{33} cm^{-2}s^{-1}





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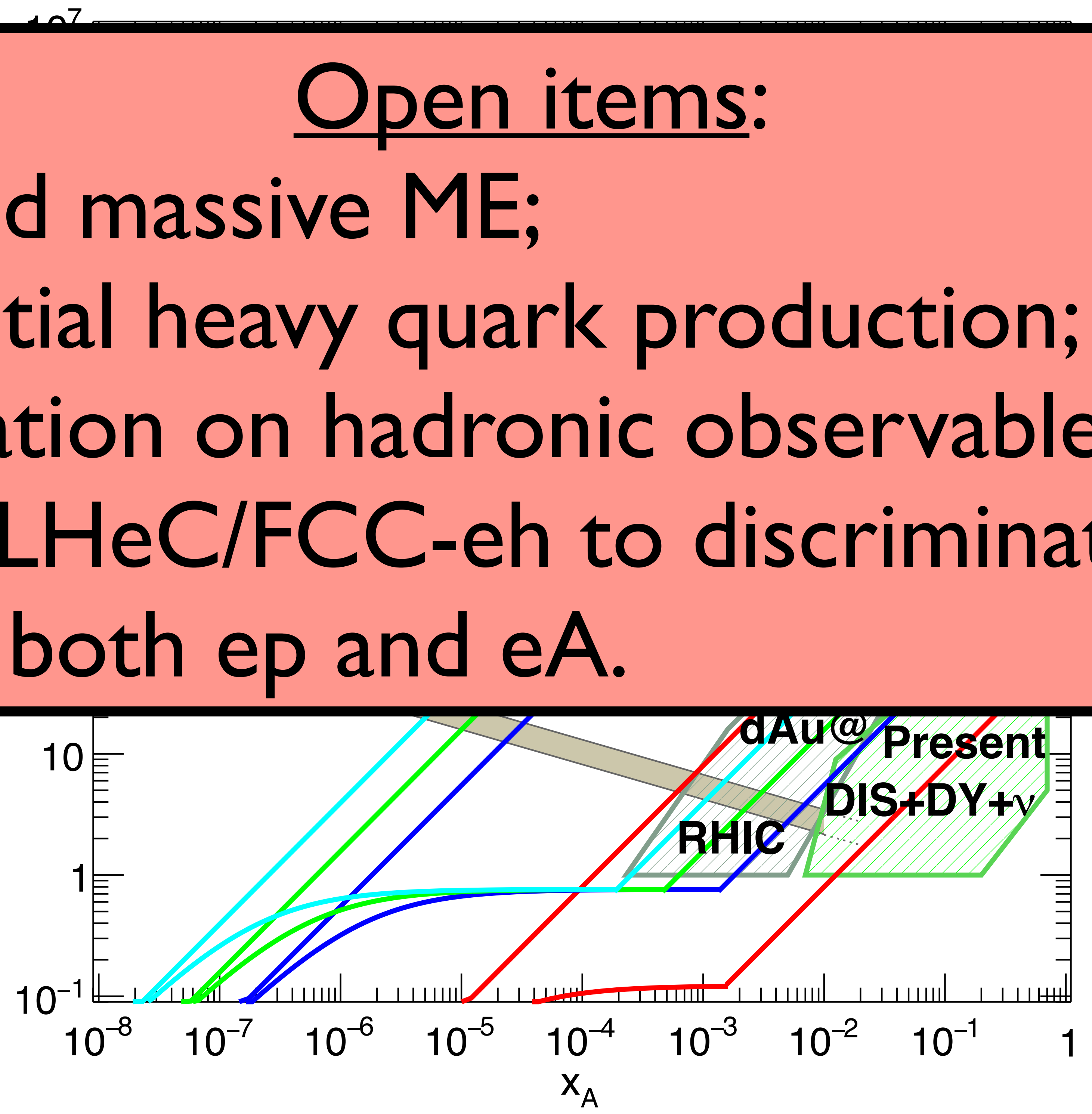
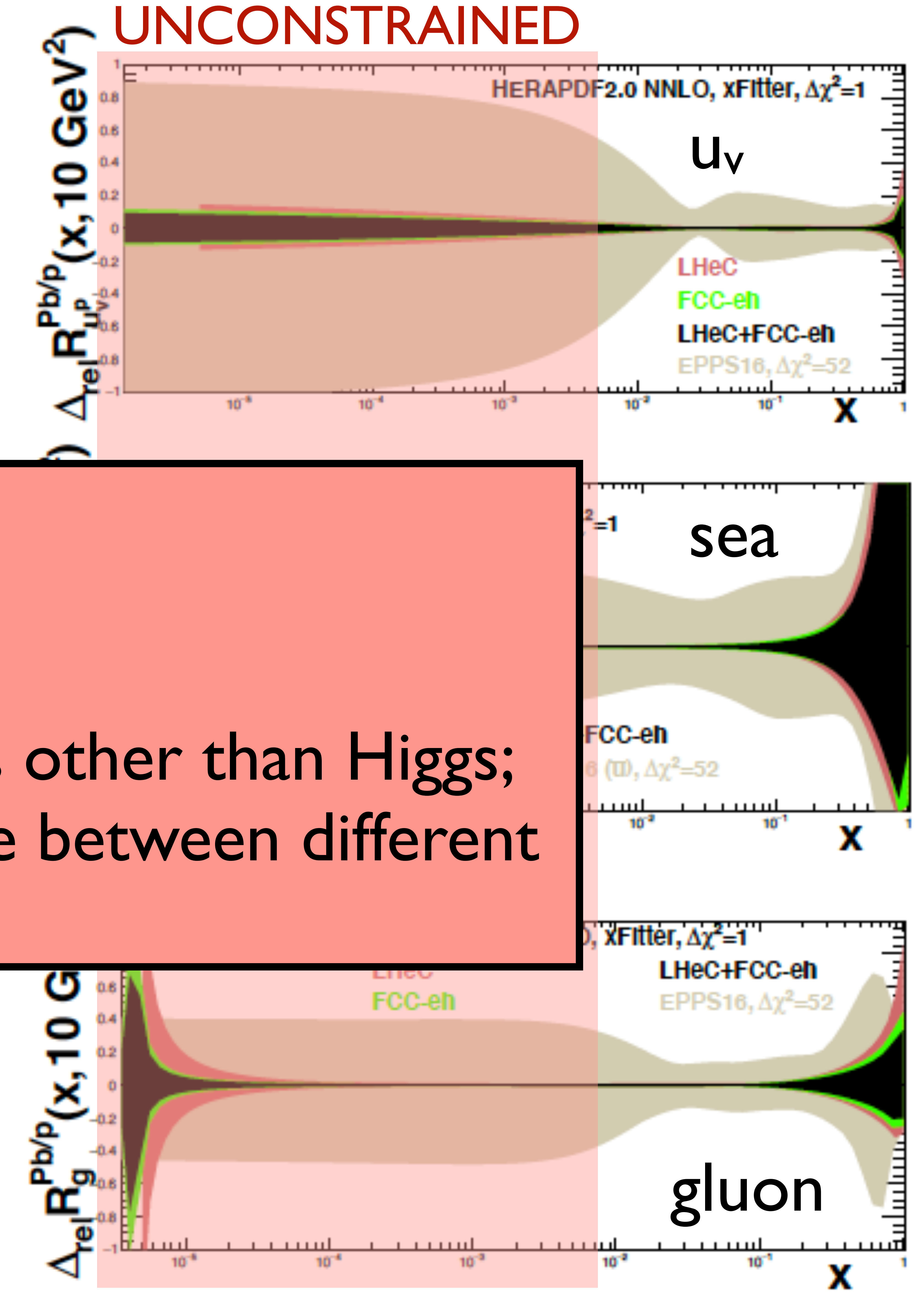




Open items:

➜ N³LO evolution and massive ME;

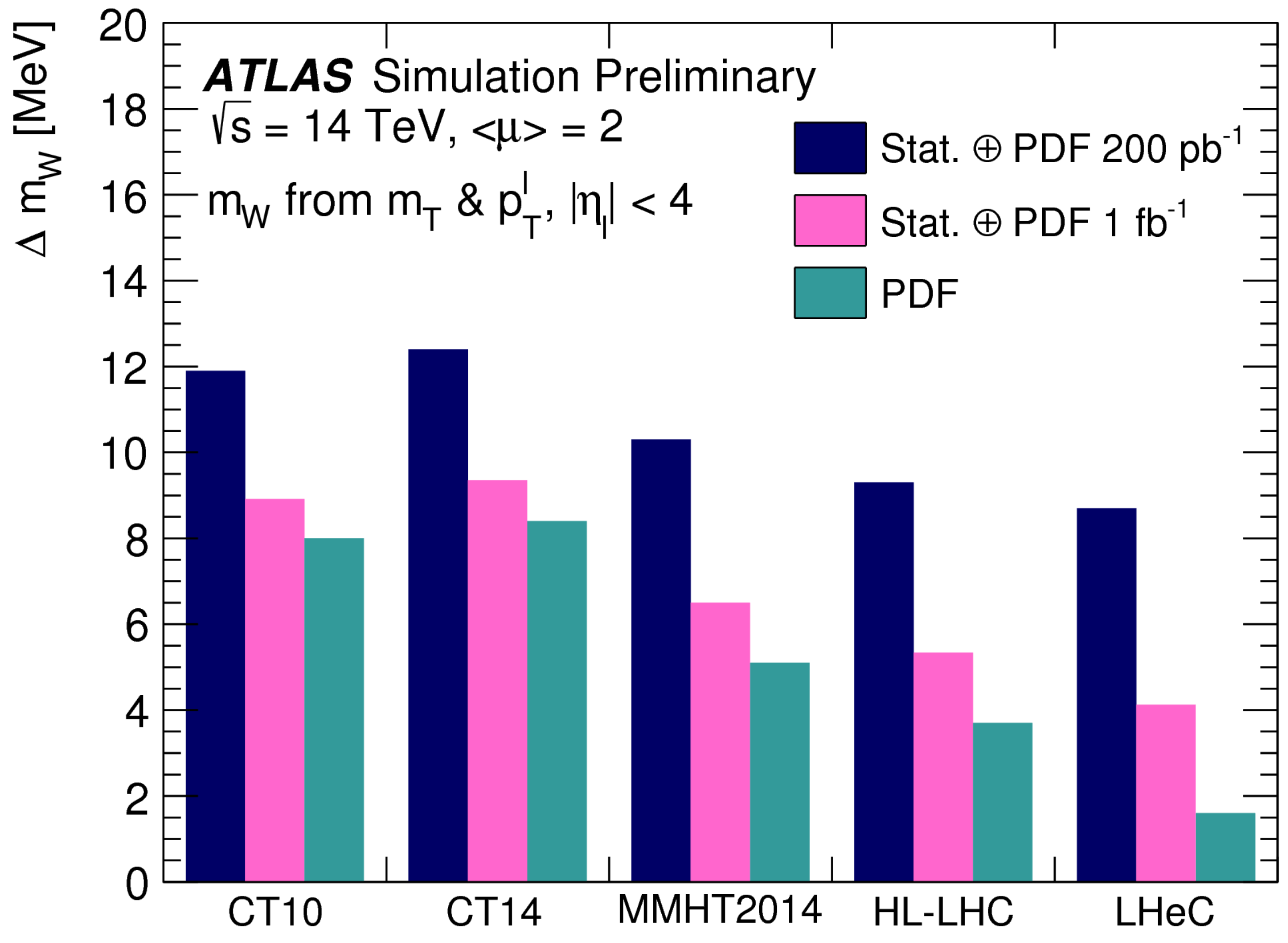
➜ NNLO for differential heavy quark production;

➜ Impact of resummation on hadronic observables other than Higgs;

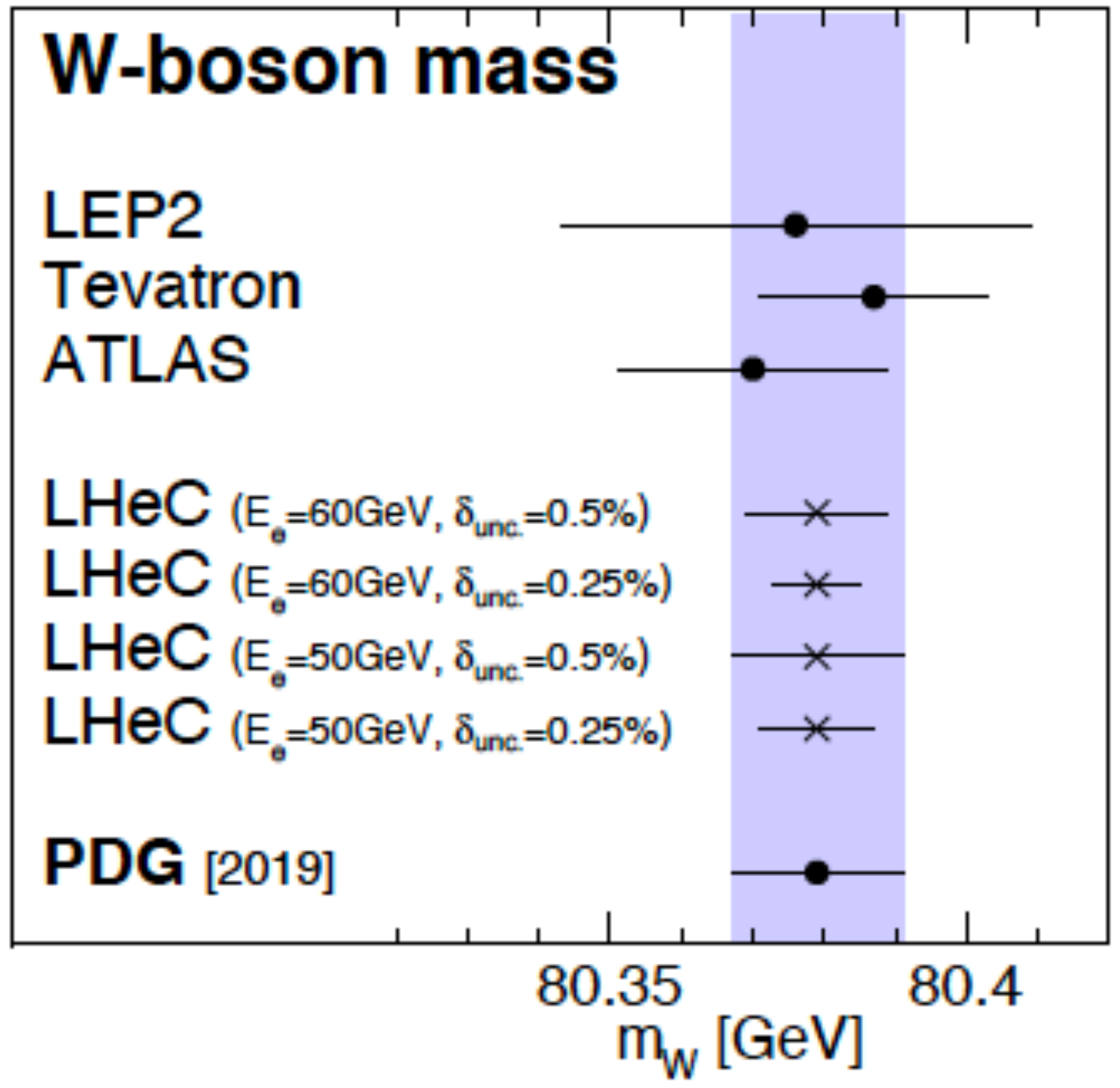
➜ Study on ability of LHeC/FCC-eh to discriminate between different small-x treatments, in both ep and eA.

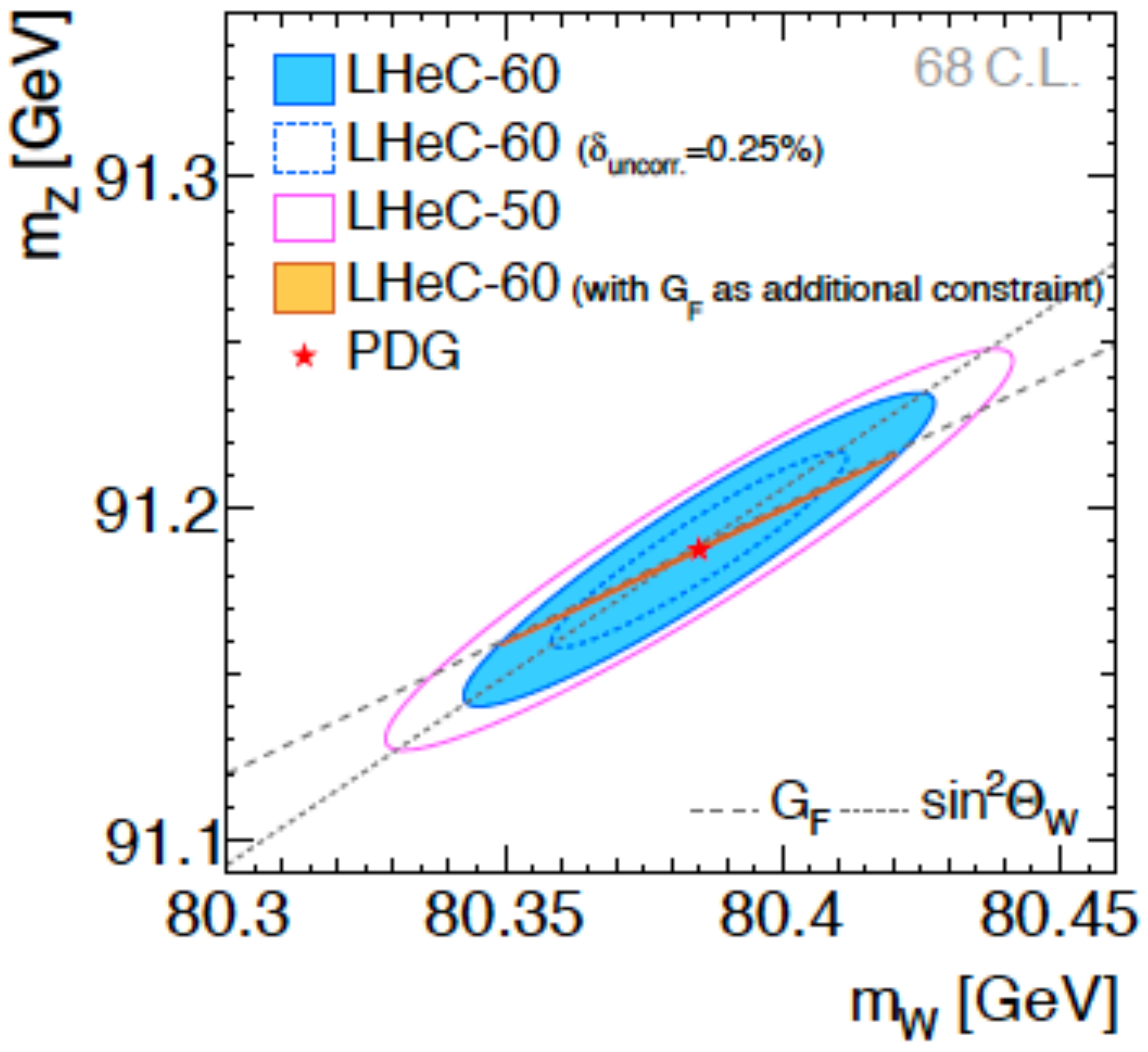
EW physics: W mass

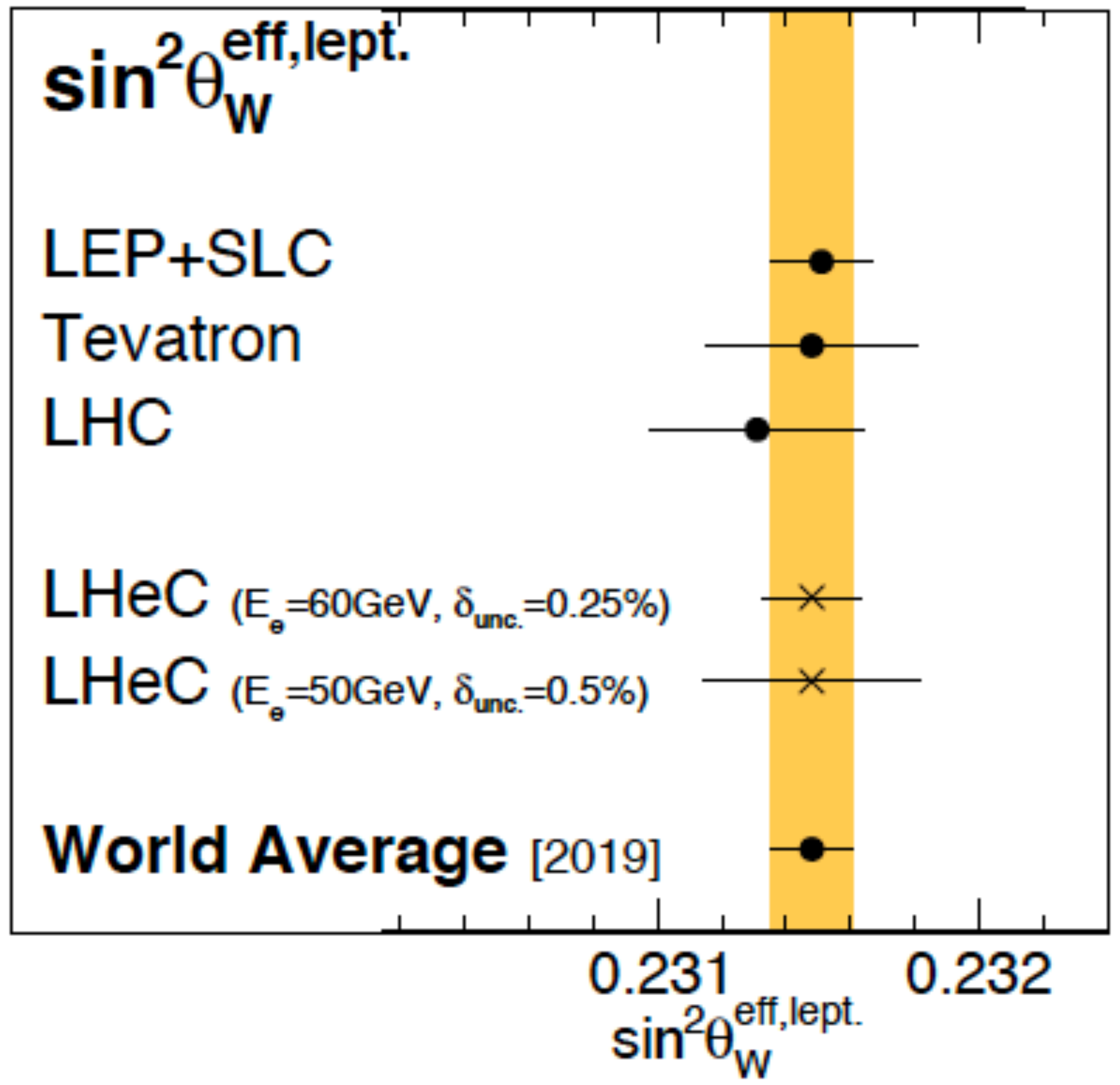
- Many EW physics opportunities (spacelike vs. timelike in e^+e^- /pp): W&Z mass, V and A neutral and charged current couplings to light quarks, $\sin^2\theta_W^{eff,l}$ to 0.1 % in a wide kinematic range,…
- LHeC will provide additional precision, though PDFs, to the determination of the measurement of W mass at HL-LHC.



$\Delta M_W = \pm 6$ MeV (HL-LHC) → ±2 MeV (HL-LHC + LHeC PDFs)





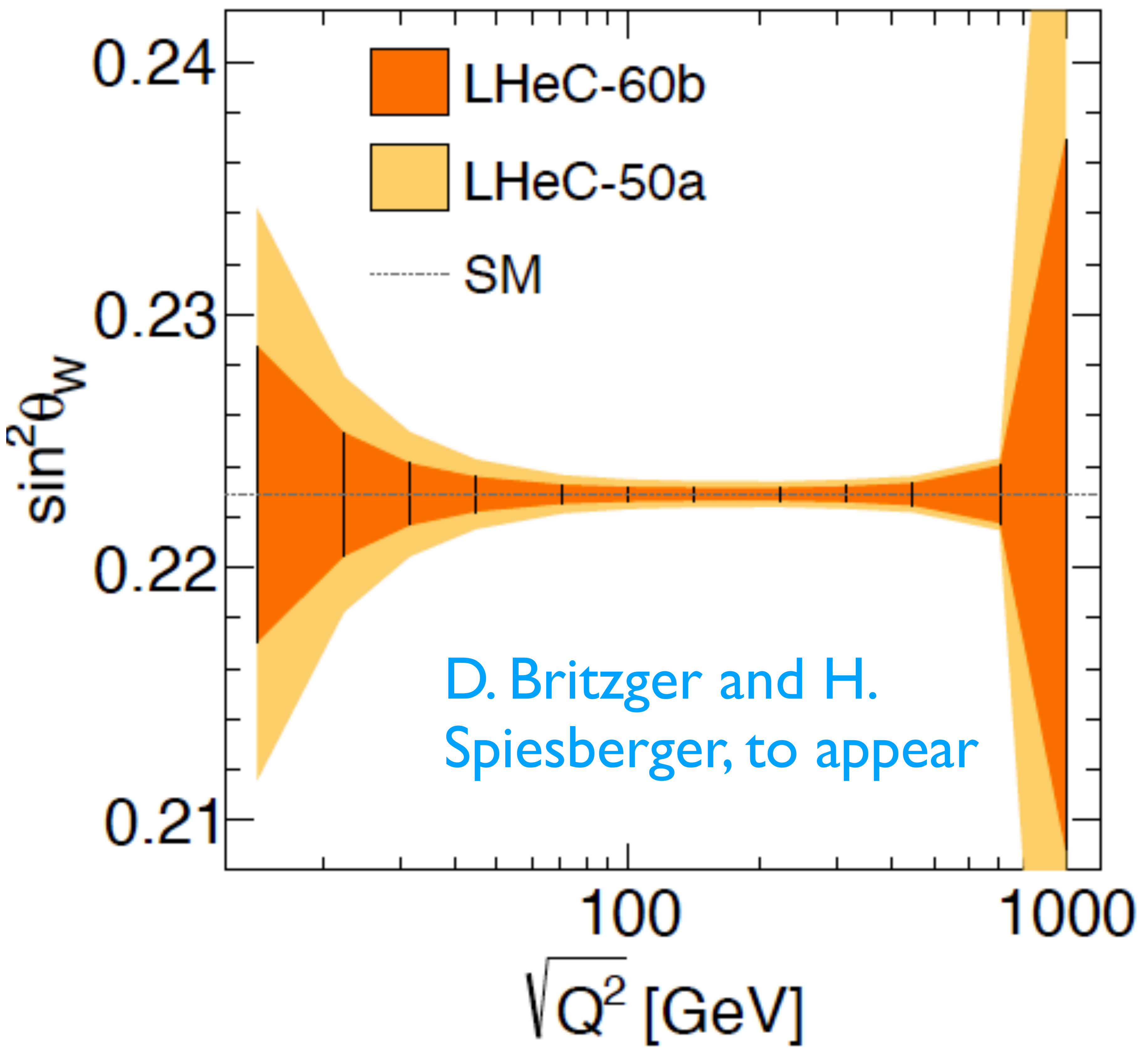


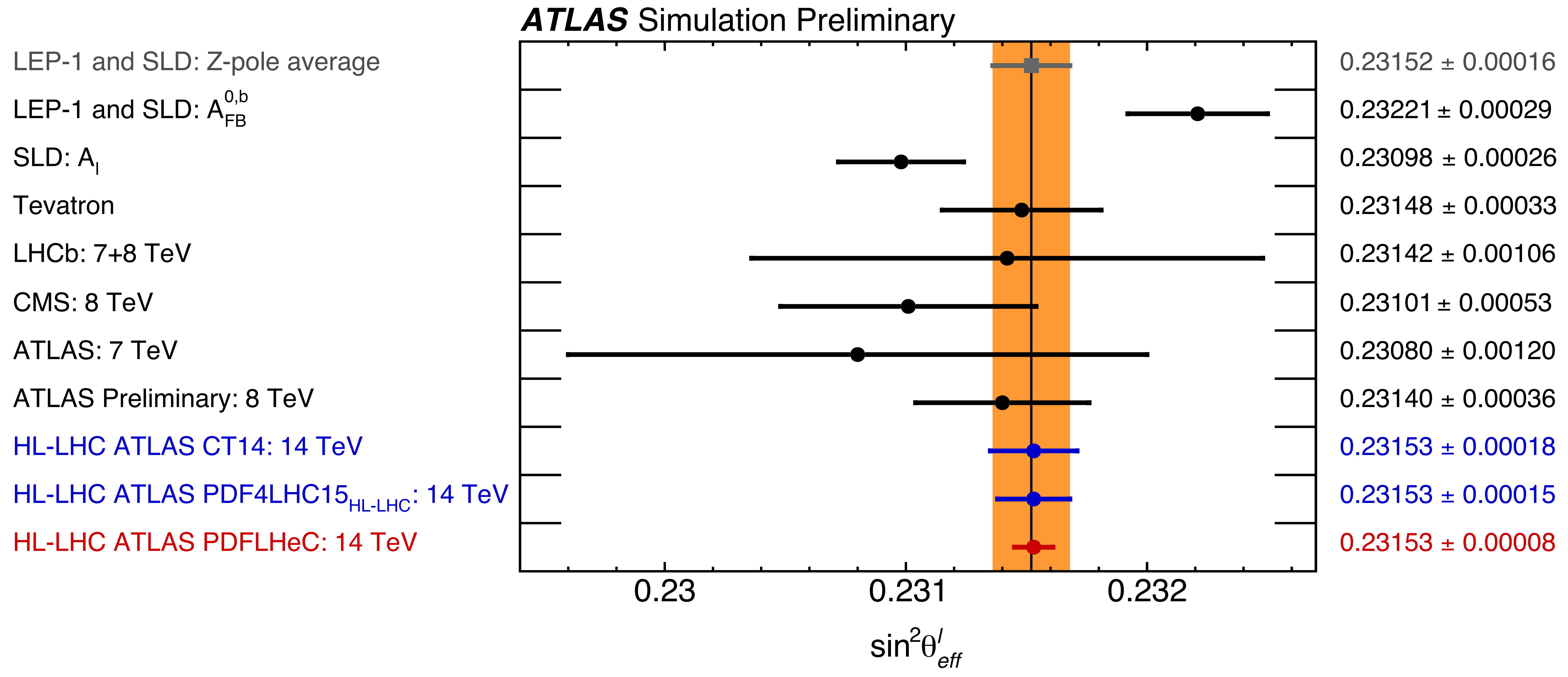
EW physics: $\sin^2\theta_W$

- Direct constraints on $\sin^2\theta_W^{eff,l}$ through higher order corrections:

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\ell}(\mu^2) = \kappa_{\mathrm{NC},\ell}(\mu^2)\sin^2\theta_{\mathrm{W}}$$

- Scale dependence through simultaneous fits with PDFs.
- Indirect measurements through improving LHC measurements (FB asymmetries).





LHeC PDFs

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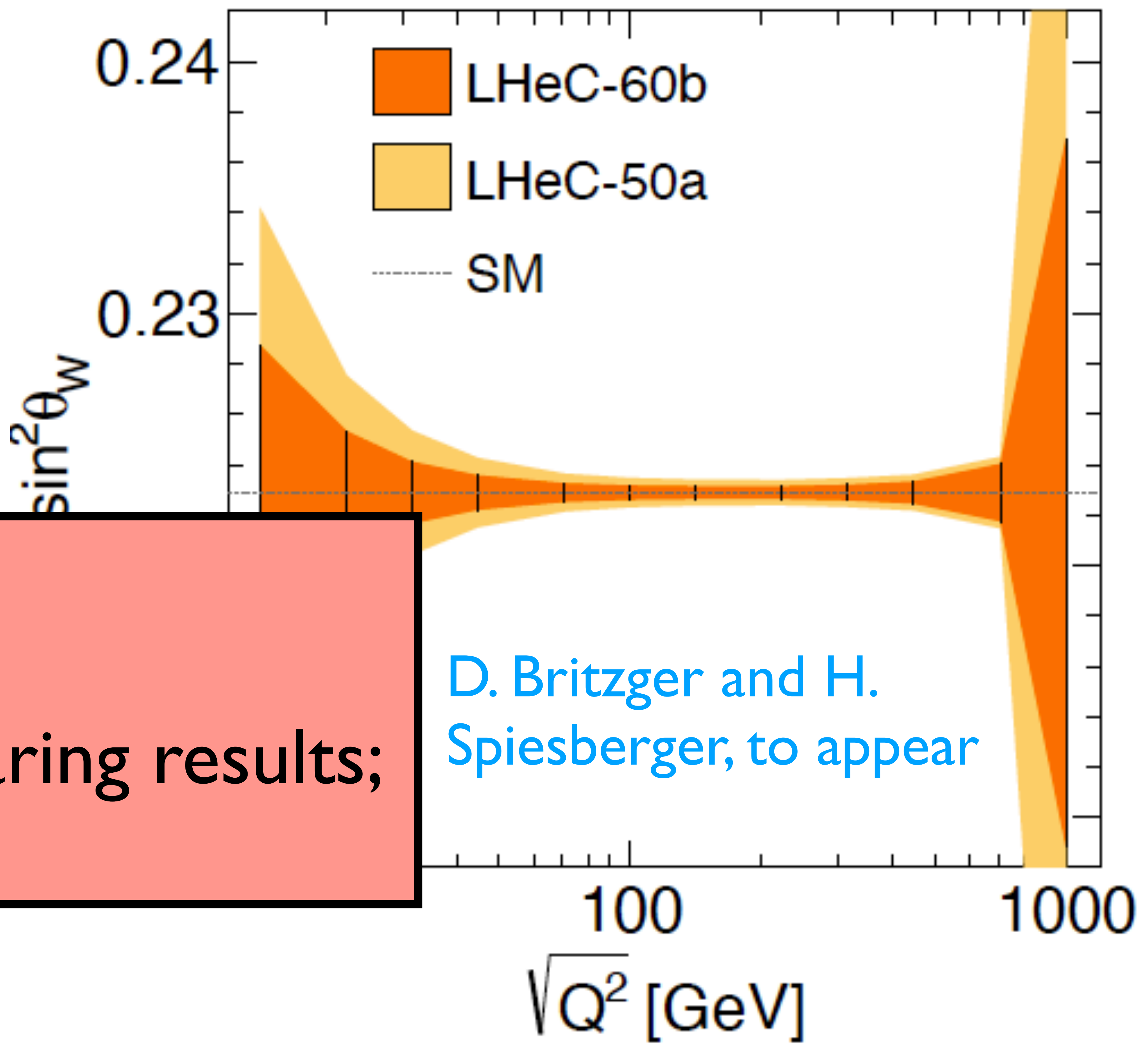
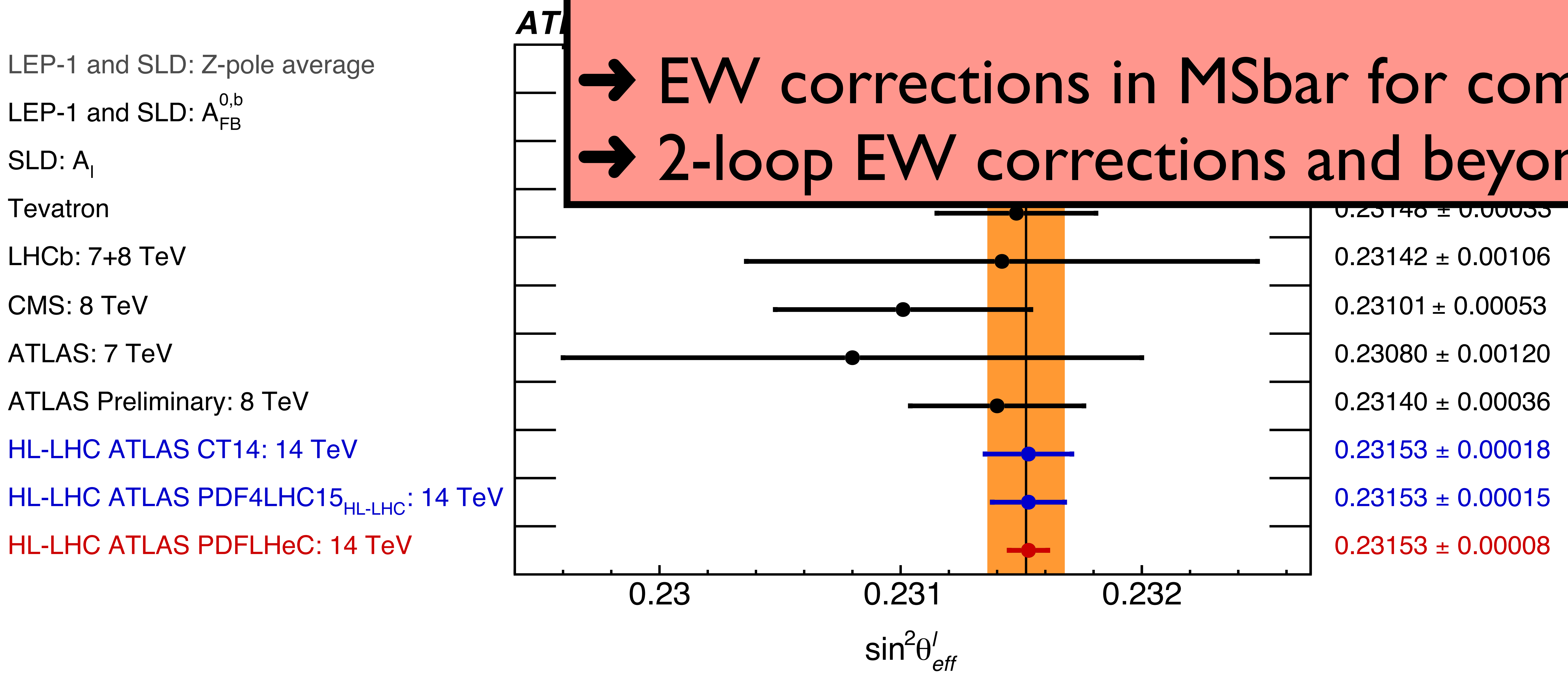


D. Britzger and H. Spiesberger, to appear

Open items:

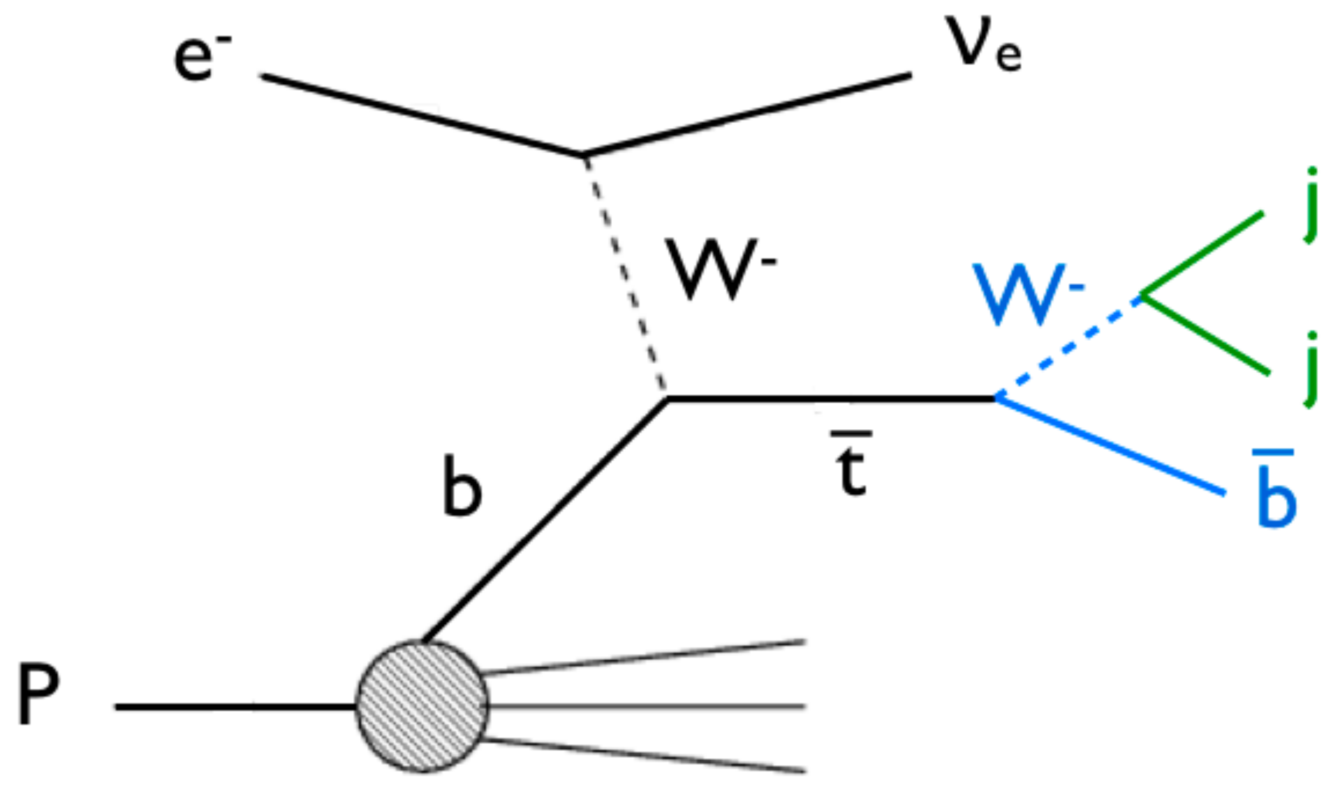
➜ EW corrections in MSbar for comparing results;
➜ 2-loop EW corrections and beyond.



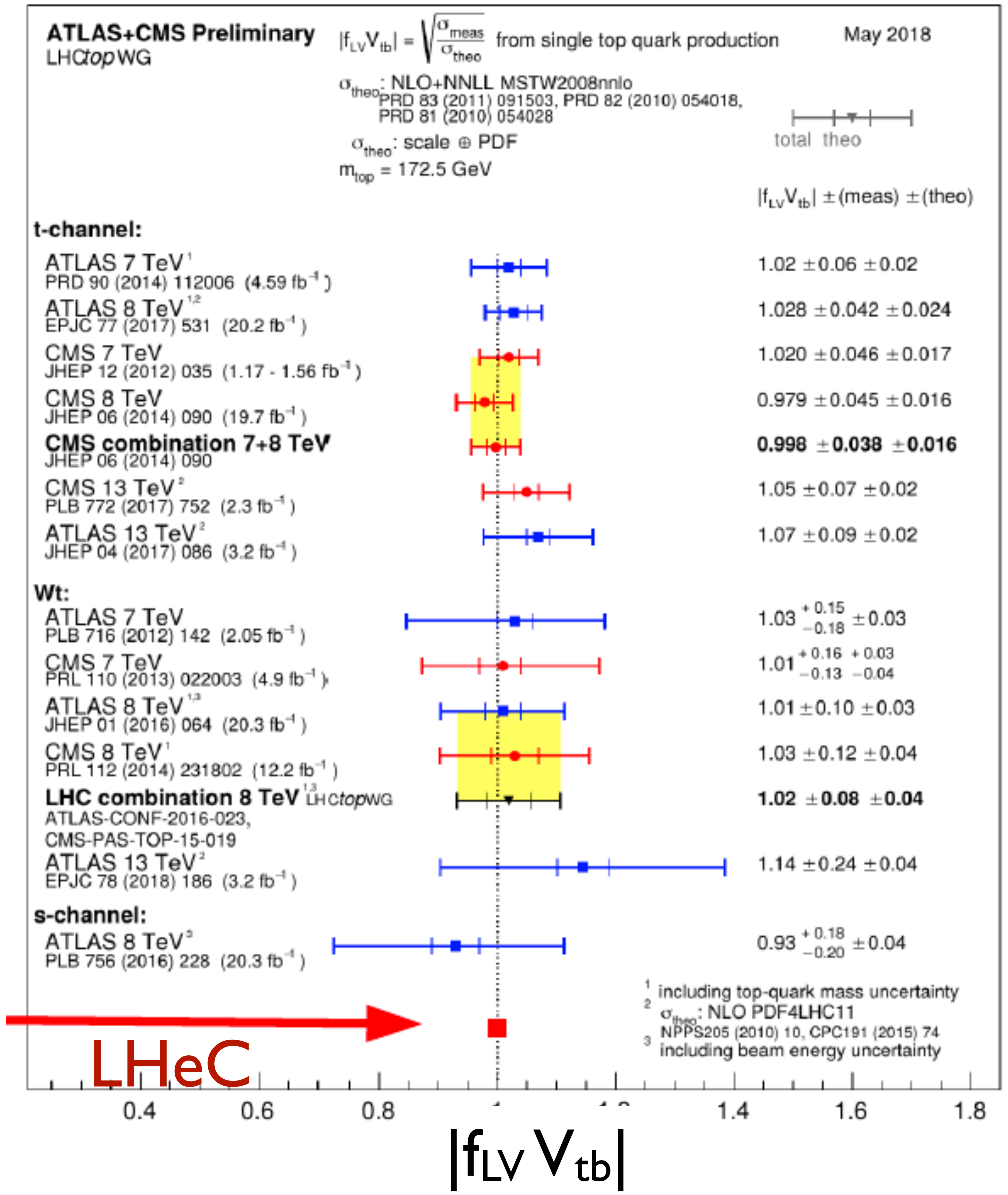
LHeC PDFs

Top physics: CKM

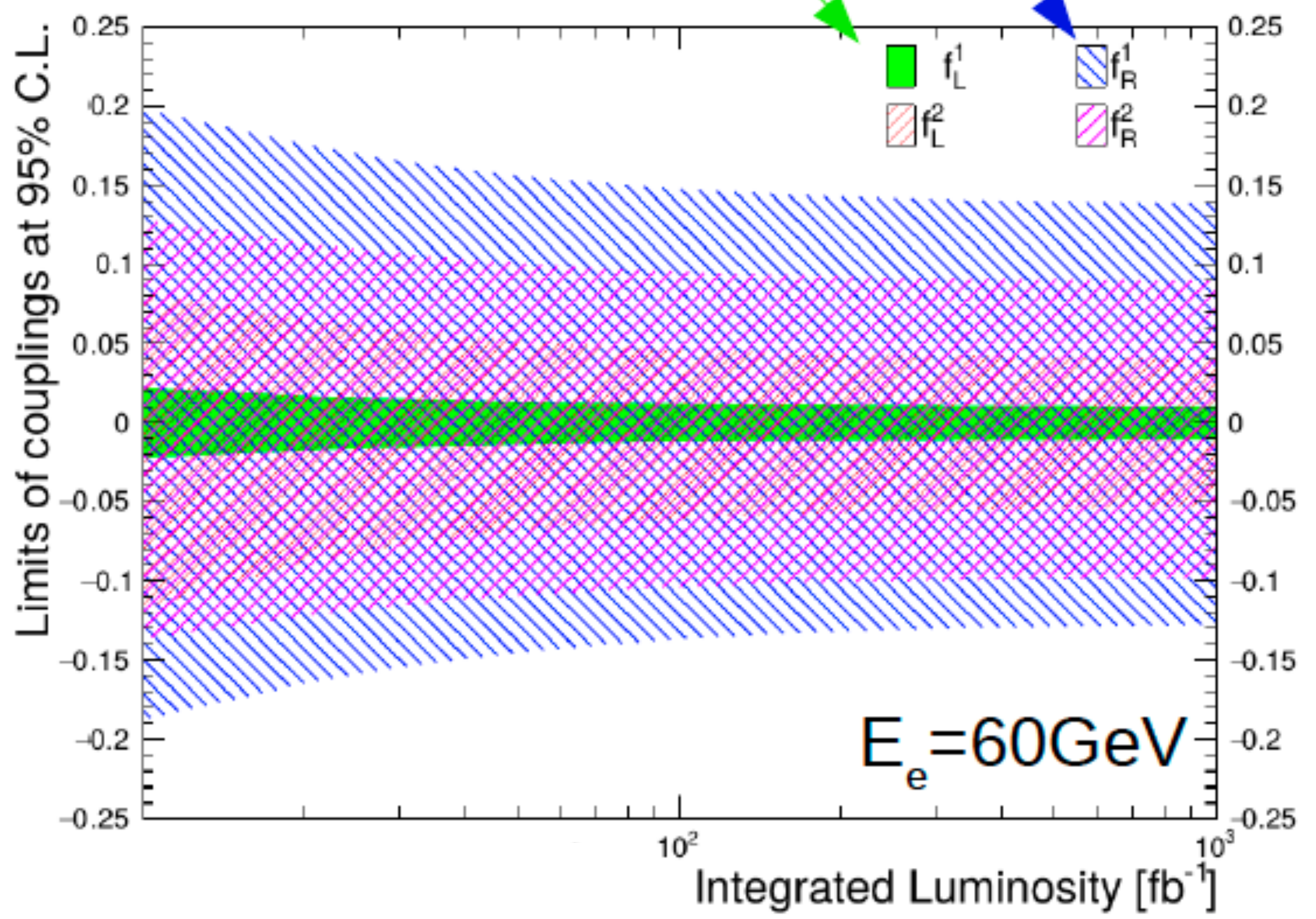
- At the LHeC, limits on several CKM matrix elements can be set using single top production: polarisation essential. Anomalous couplings can be probed, limits competitive with HL-LHC.



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



$$\mathscr{L}_{Wtb} = \frac{g}{\sqrt{2}}\Big[W_\mu \bar{t}\gamma^\mu (V_{tb}\, f_1^L P_L + f_1^R P_R) b - \frac{1}{2\, m_W} W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_2^L P_L + f_2^R P_R) b\Big] + h.c.$$



Top physics: FCNC

- At the LHeC, limits on several CKM matrix elements can be set using single top production: polarisation essential. Anomalous couplings can be probed, limits competitive with HL-LHC.
- Also top FCNC or CP violation in top Yukawa couplings.

Top quark flavor changing neutral currents (FCNC)

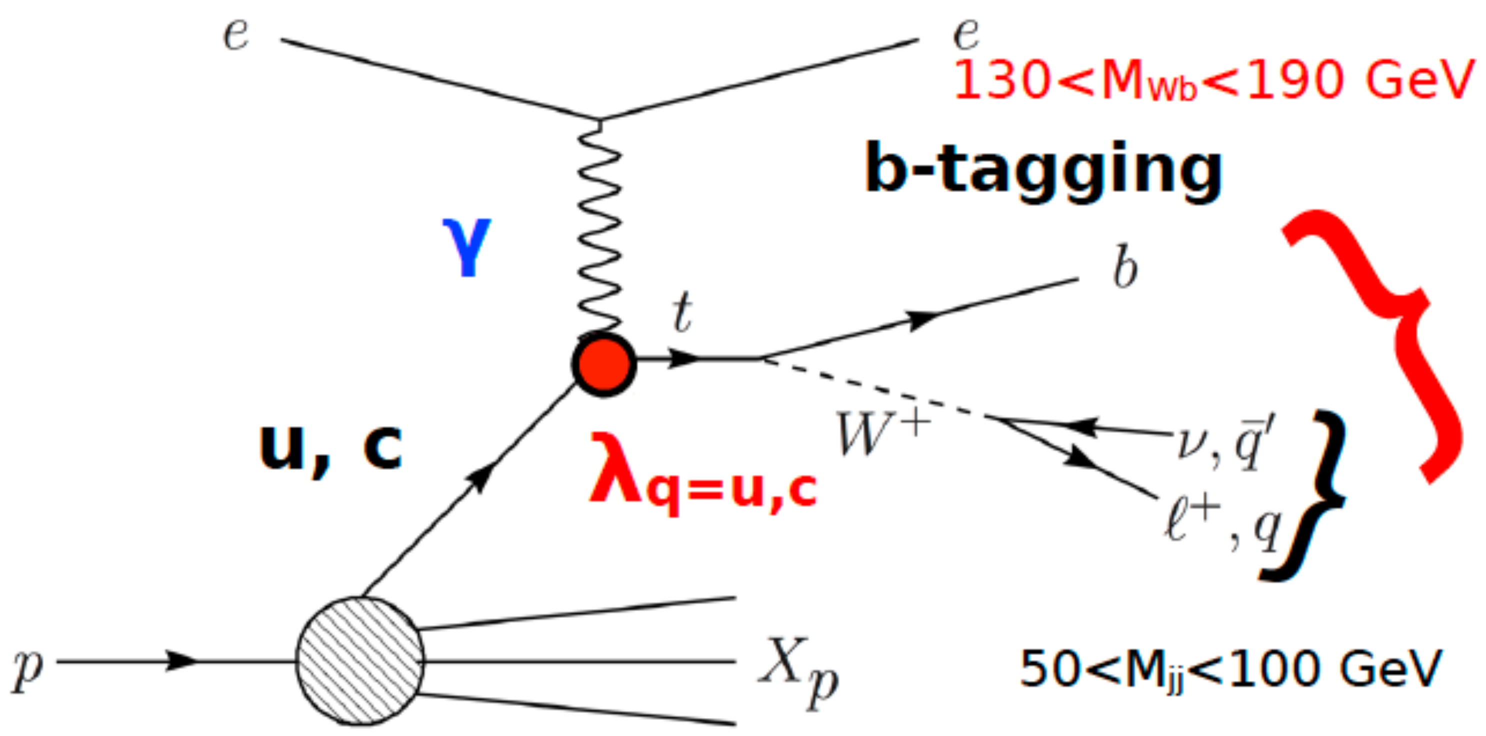
→ Extremely suppressed in SM

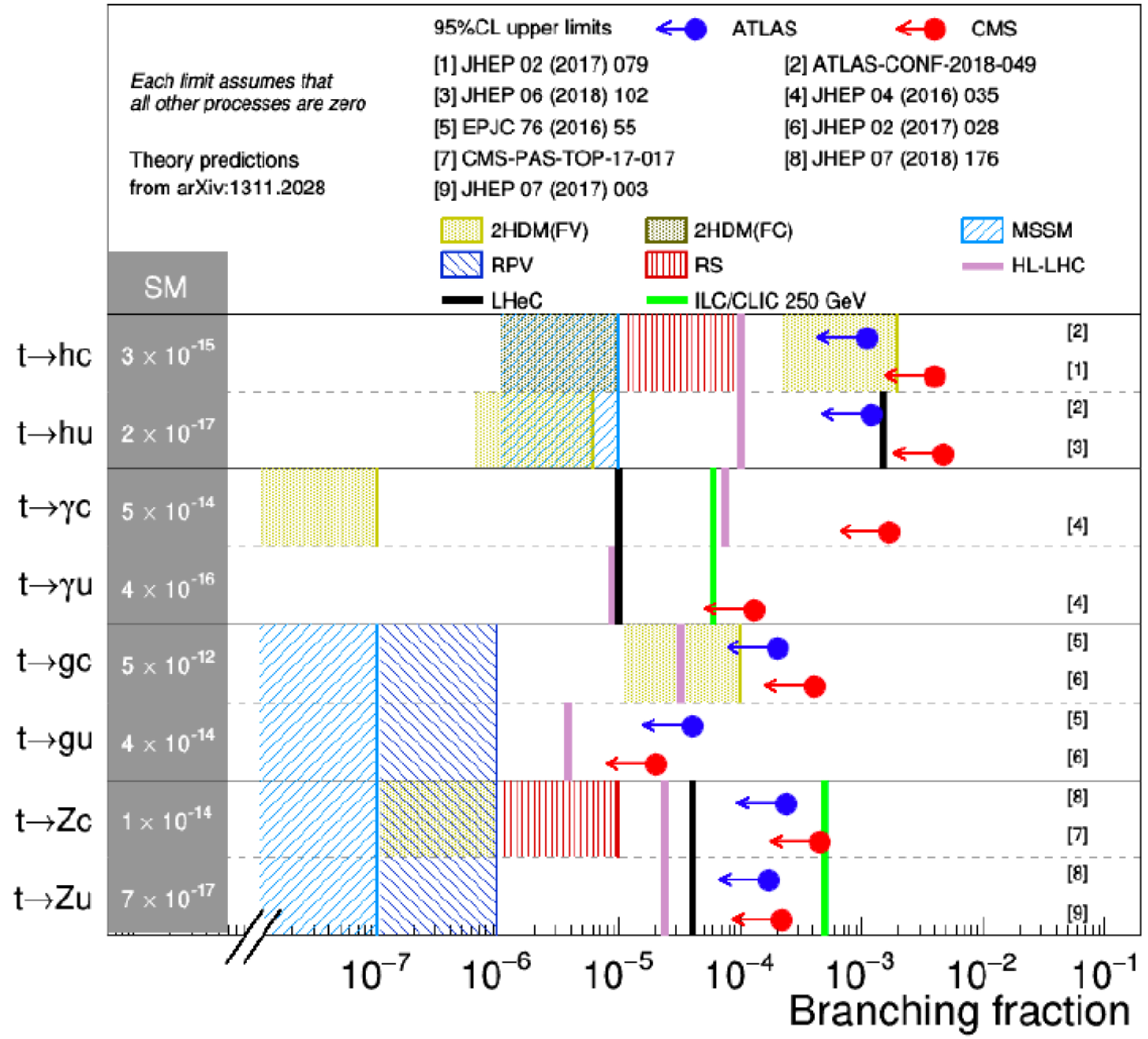
Enhancement through BSM contributions

→ effective Lagrangian

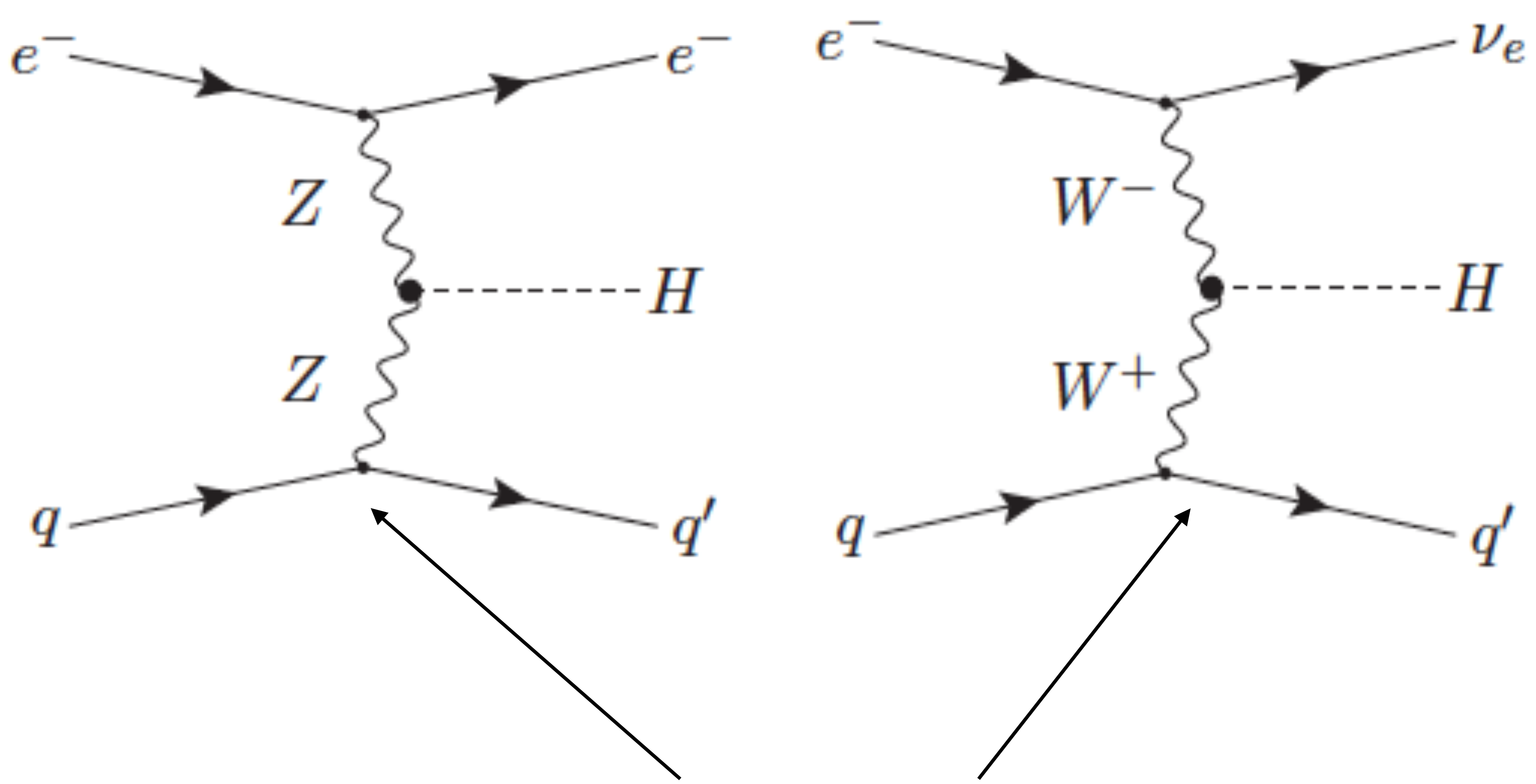
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5) q A_{\mu\nu} + h.c.$$

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)





Higgs physics: cross sections



Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P = -0.8)$	fb	197	372	516	1038
σ_{NC} $(P = -0.8)$	fb	24	48	70	149
σ_{CC} $(P = 0)$	fb	110	206	289	577
σ_{NC} $(P = 0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15

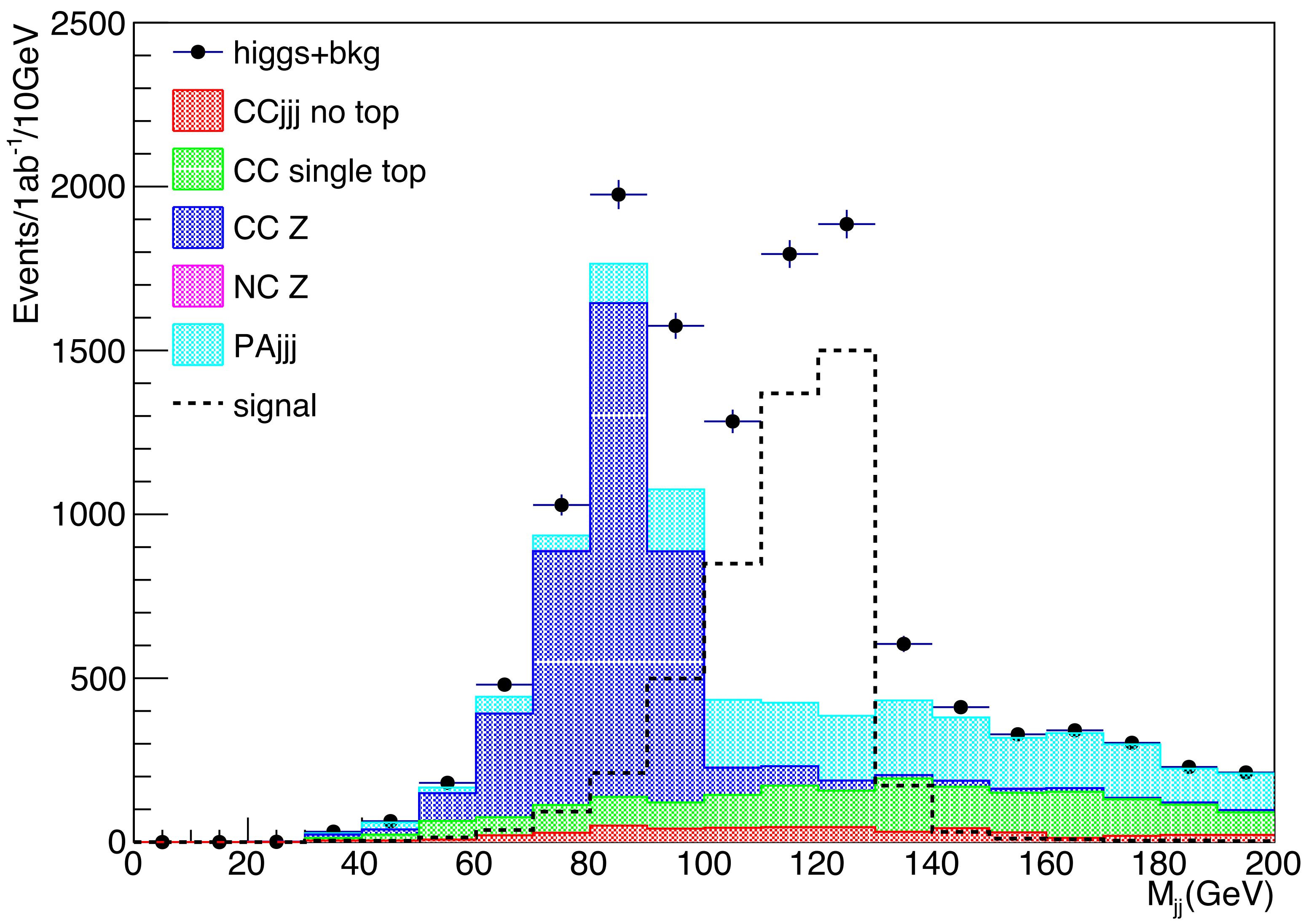
- Cross section for NC and CC Higgs production through VBF makes study possible with foreseen luminosities; initial estimate of g_{HHH} to 20 % accuracy at the FCC-eh.

- Large Higgs dataset for precision measurements.

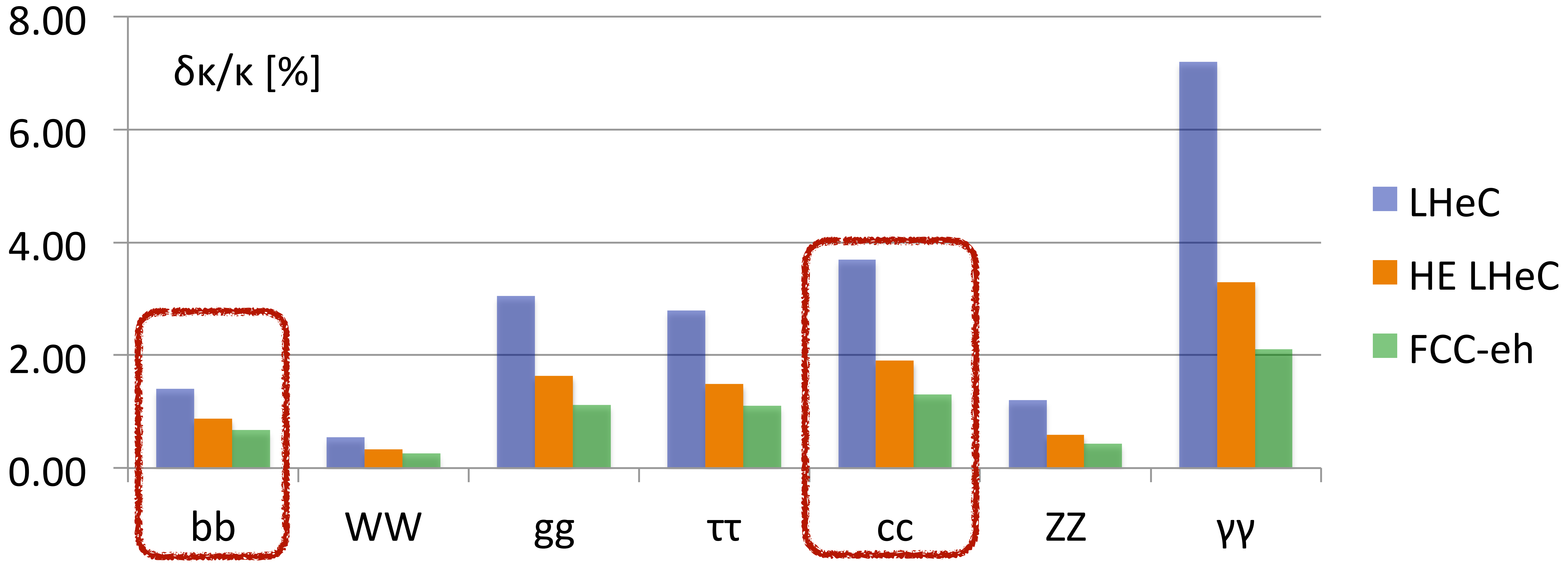
Higgs to bb and cc in ep:

- Decays to bb and cc, P=-0.8, detector level analysis with HF tagger, efficiency 60-75 (10) % for b(c)-tagged jets.

LHeC:	1 ab^{-1}	E_p=7 TeV
HE LHeC:	2 ab^{-1}	E_p=13 TeV
FCC-eh:	2 ab^{-1}	E_p=50 TeV

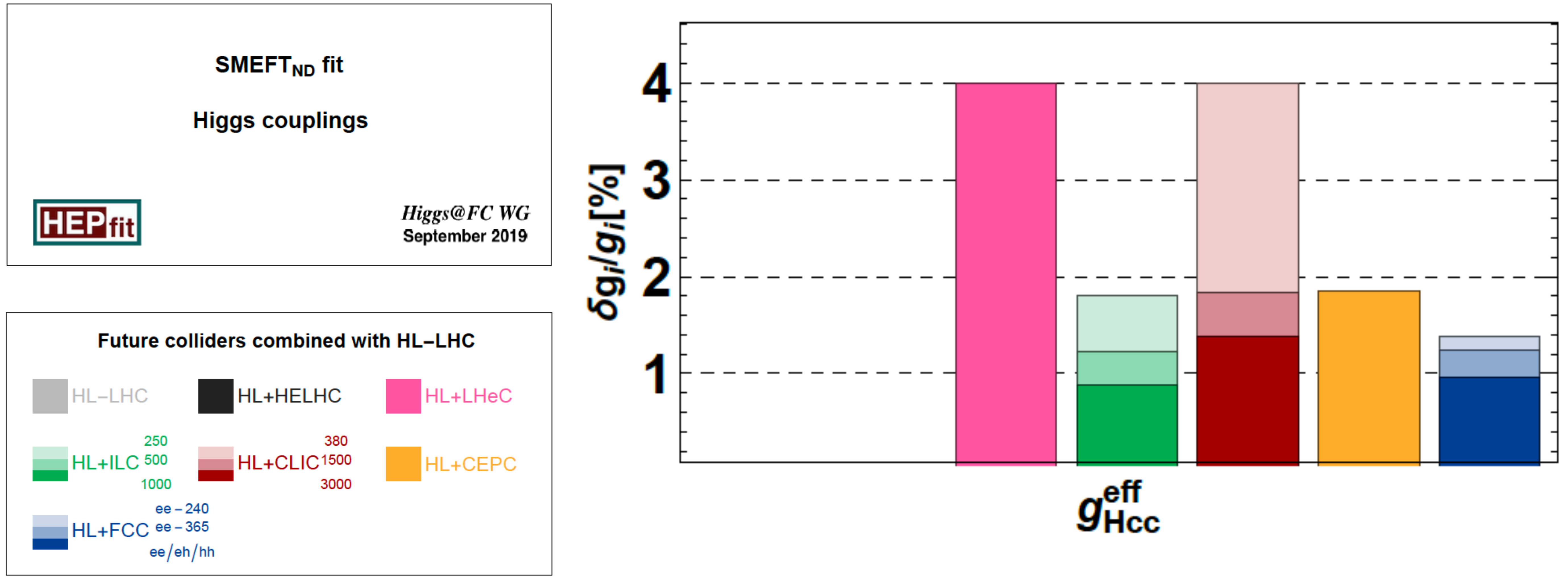


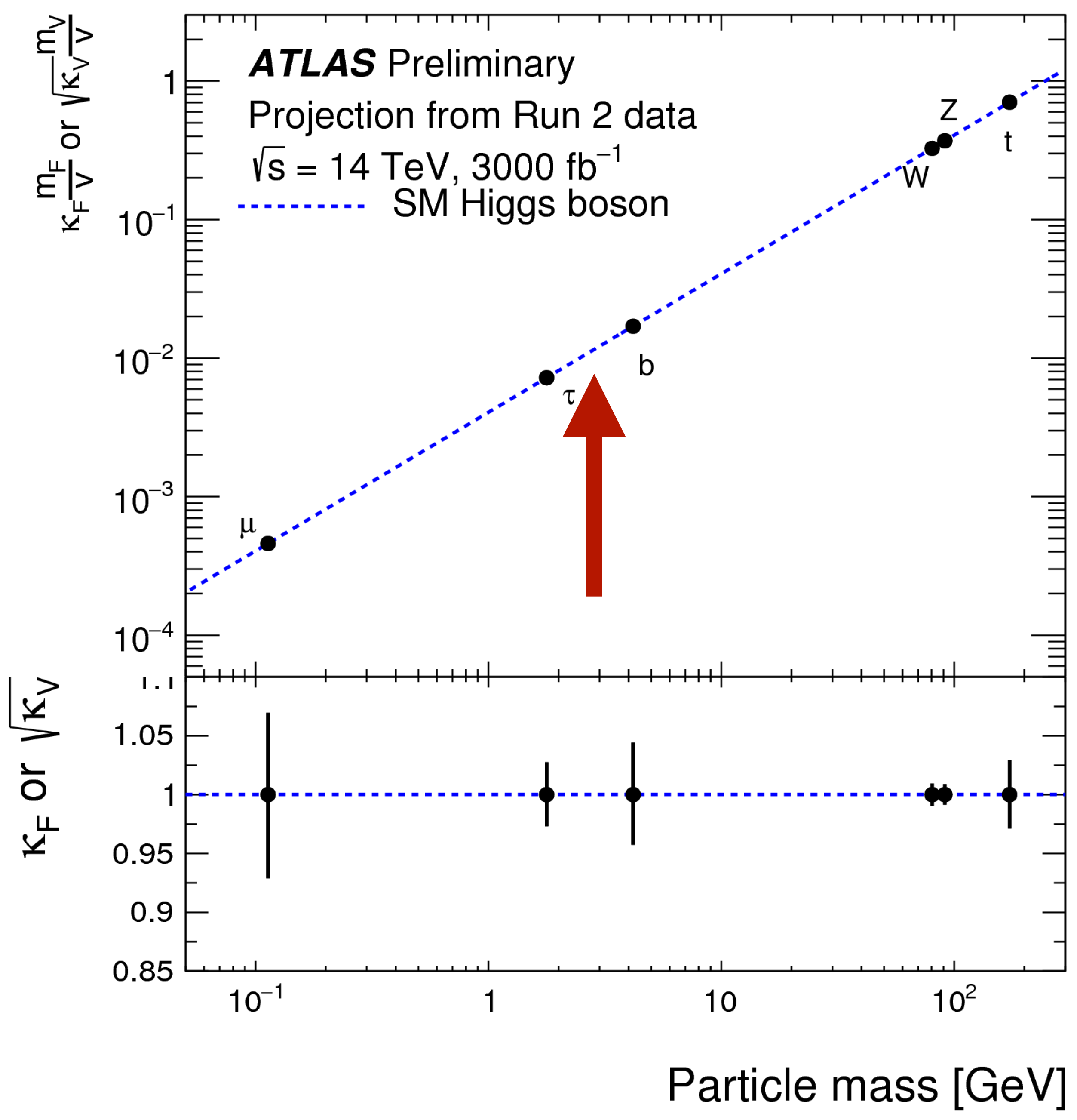
$$\sigma^i_{CC} = \sigma_{CC}\, br_i \cdot \kappa_W^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j} \qquad \sigma^i_{NC} = \sigma_{NC}\, br_i \cdot \kappa_Z^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j}$$

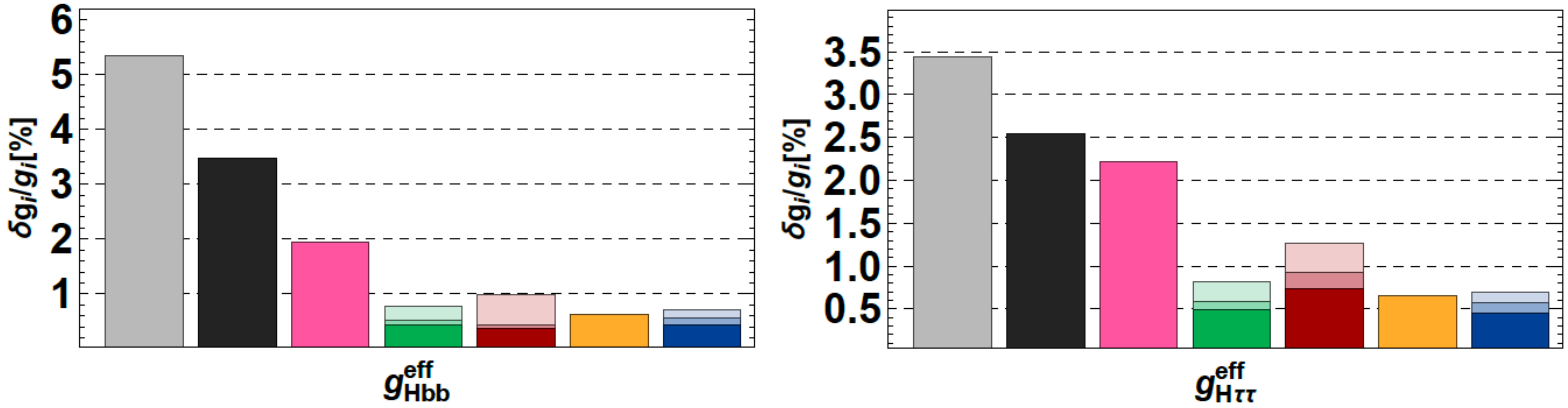


Higgs to cc at ep and pp:

- No real sensitivity for H→cc expected at HL-LHC.
- HL-LHC+LHeC and HL+FCC ee+eh/hh, dominated by eh, will be very effective.
- Improvements in H→bb and H→ττ.





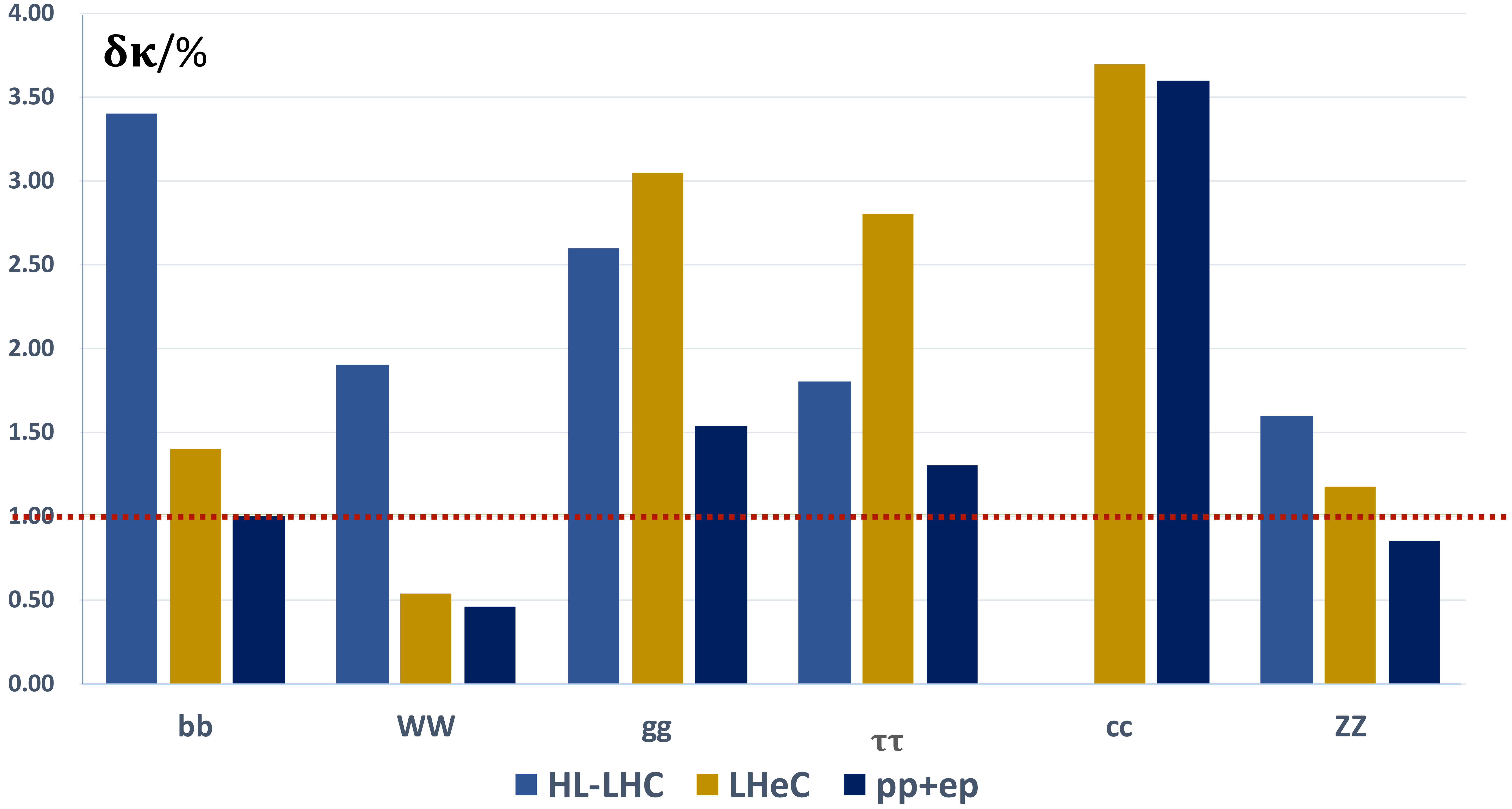


Higgs physics: ep+pp combination

- ep+pp combination reaches below 1% for dominant channels

- ep adds charm.

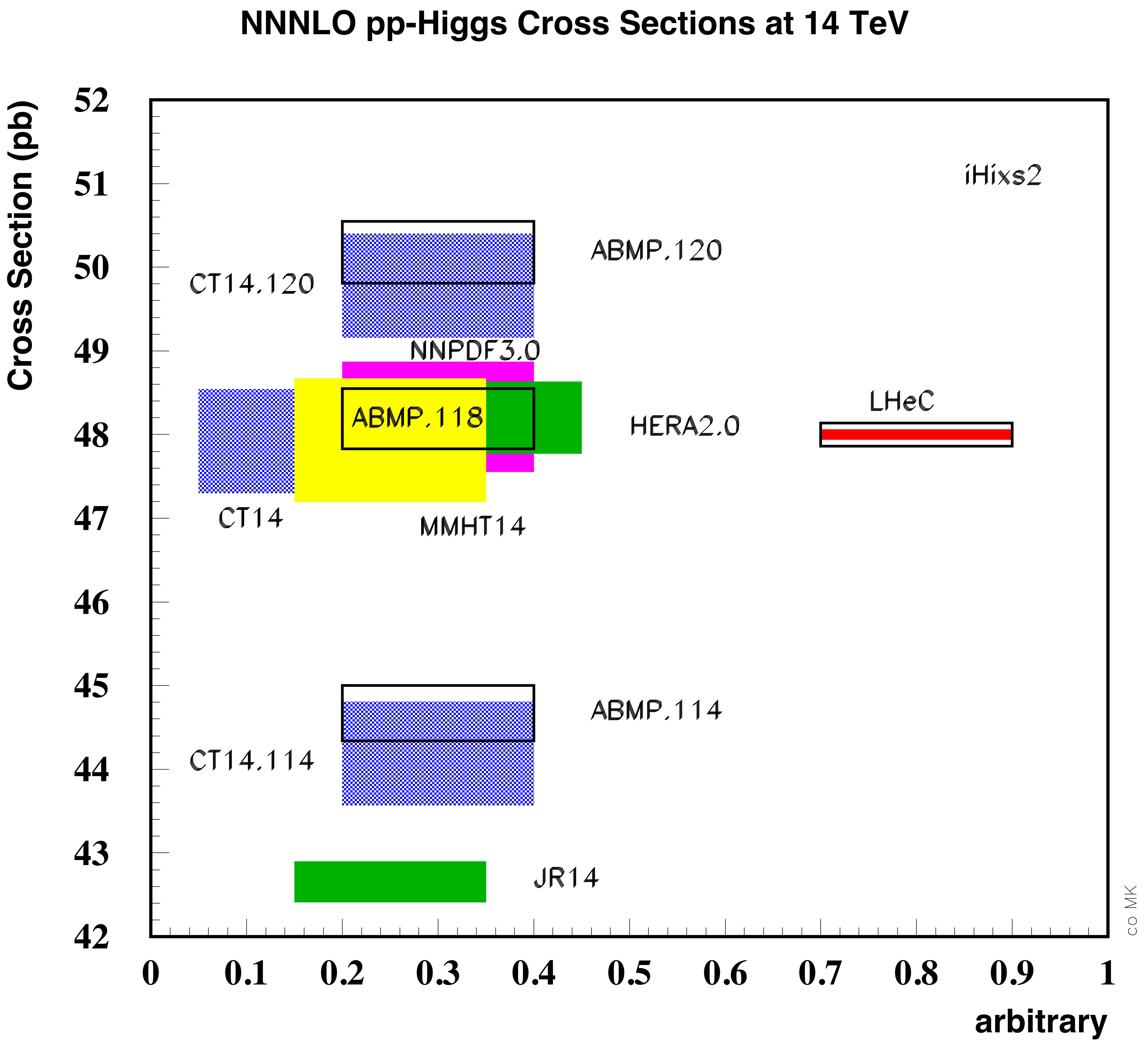
- SMEFT analysis ongoing.



Impact of LHeC on Higgs Xsection:

- Calculation in all production modes improved by better PDFs and α_s.

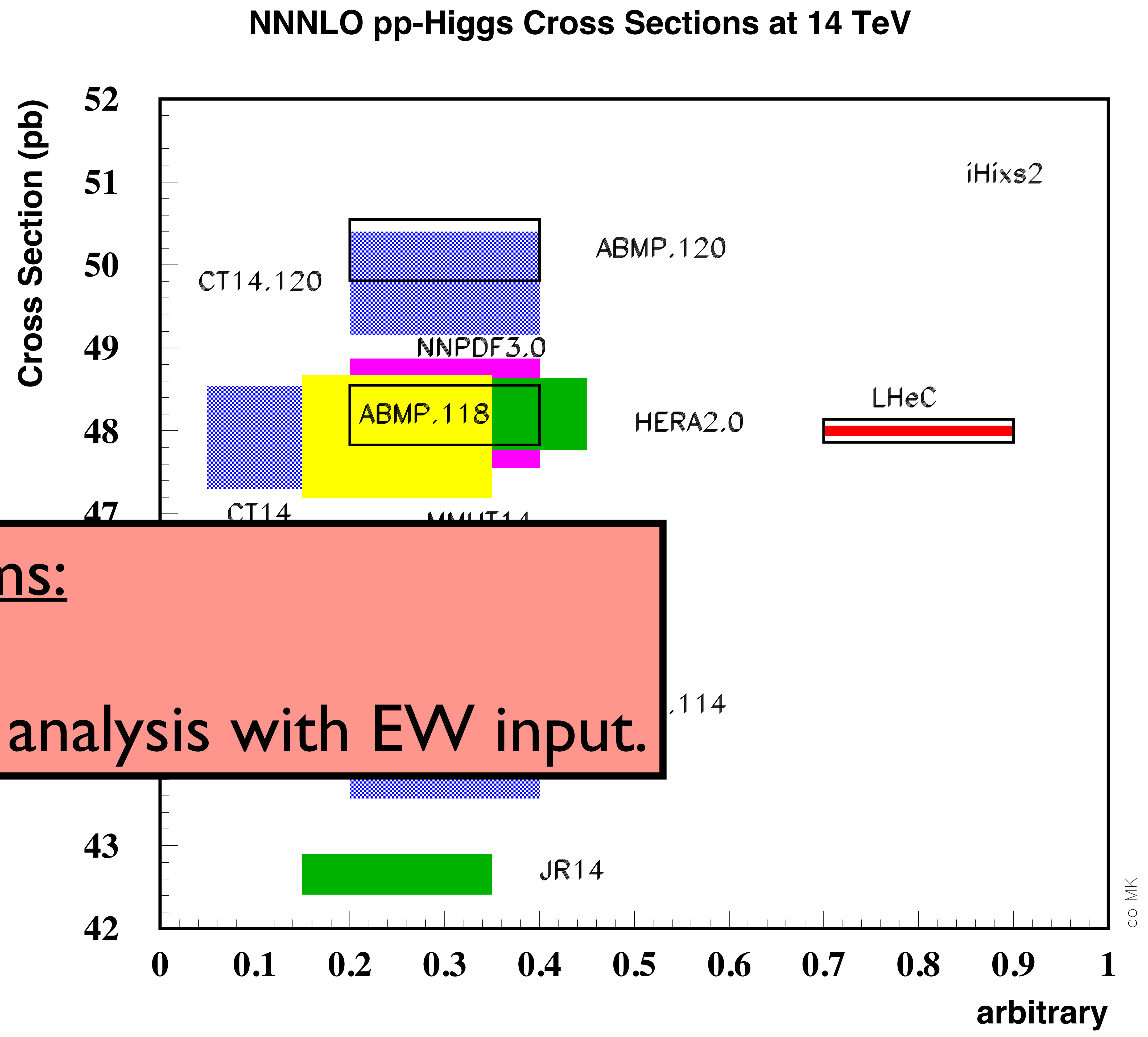
Process	σ_H [pb]	$\Delta\sigma_{\text{scales}}$	$\Delta\sigma_{\text{PDF}+\alpha_s}$ HL-LHC PDF	$\Delta\sigma_{\text{PDF}+\alpha_s}$ LHeC PDF
Gluon-fusion	54.7	5.4 %	3.1 %	0.4 %
Vector-boson-fusion	4.3	2.1 %	0.4 %	0.3 %
$pp \to WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \to ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \to t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %



Cross sections of Higgs production calculated to N^{3}LO using the iHix program for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side).

Impact of LHeC on Higgs Xsection:

- Calculation in all production modes improved by better PDFs and α_s.



Cross sections of Higgs production calculated to N^3LO using the iHix program for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side).

Open items:

➜ Full HL-LHC+LHeC SMEFT analysis with EW input.

Process	σ_H [			
Gluon-fusion	54.7	5.4 %	3.1 %	0.4 %
Vector-boson-fusion	4.3	2.1 %	0.4 %	0.3 %
$pp \to WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \to ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \to t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %

BSM physics:

- ep collider is ideal to study common features of electrons and quarks with EW / VBF production, LQ, forward objects, long-lived particles.

- BSM programme at ep aims to:

  ➜ Explore new and/or challenging scenarios.

  ➜ Characterize hints for new physics if some excess or deviations from the SM are found at pp colliders.

- Differences and complementarities with pp colliders.

- Some promising aspects:

  ➜ small background due to absence of QCD interaction between e and p;

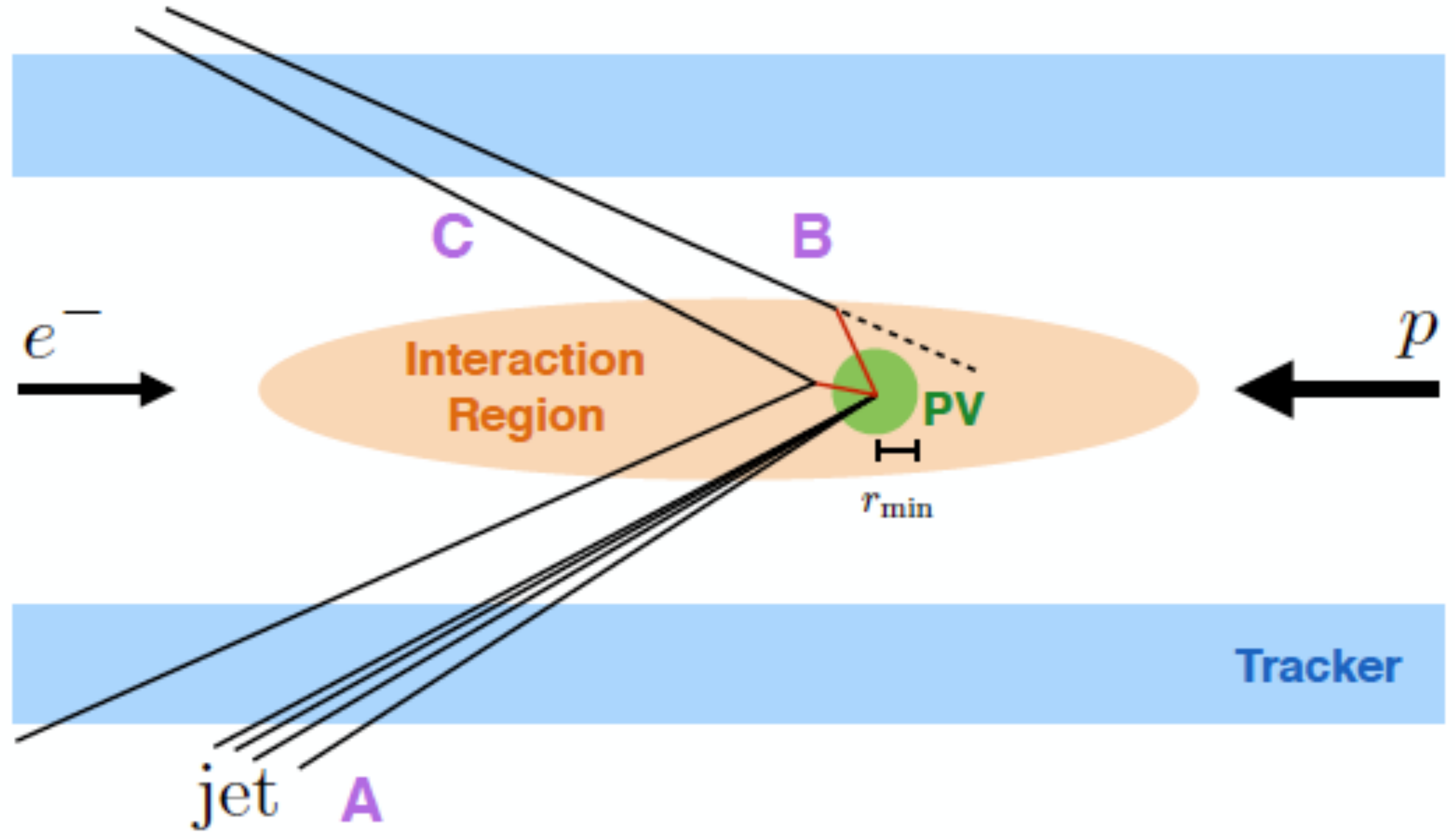
  ➜ very low pileup.

- Some difficult aspects: low production rate for NP processes due to small E_{cm}.

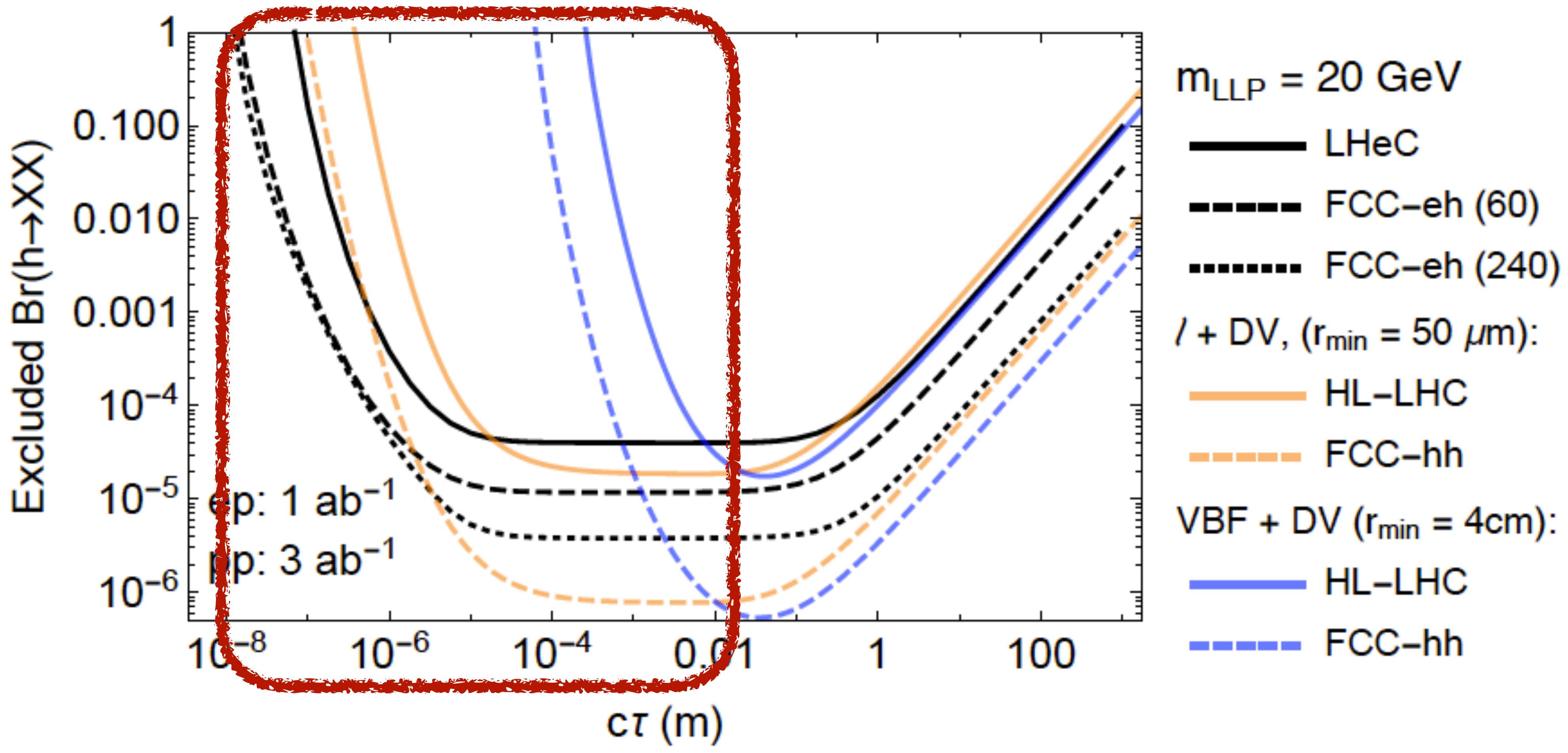
- Here only some examples…

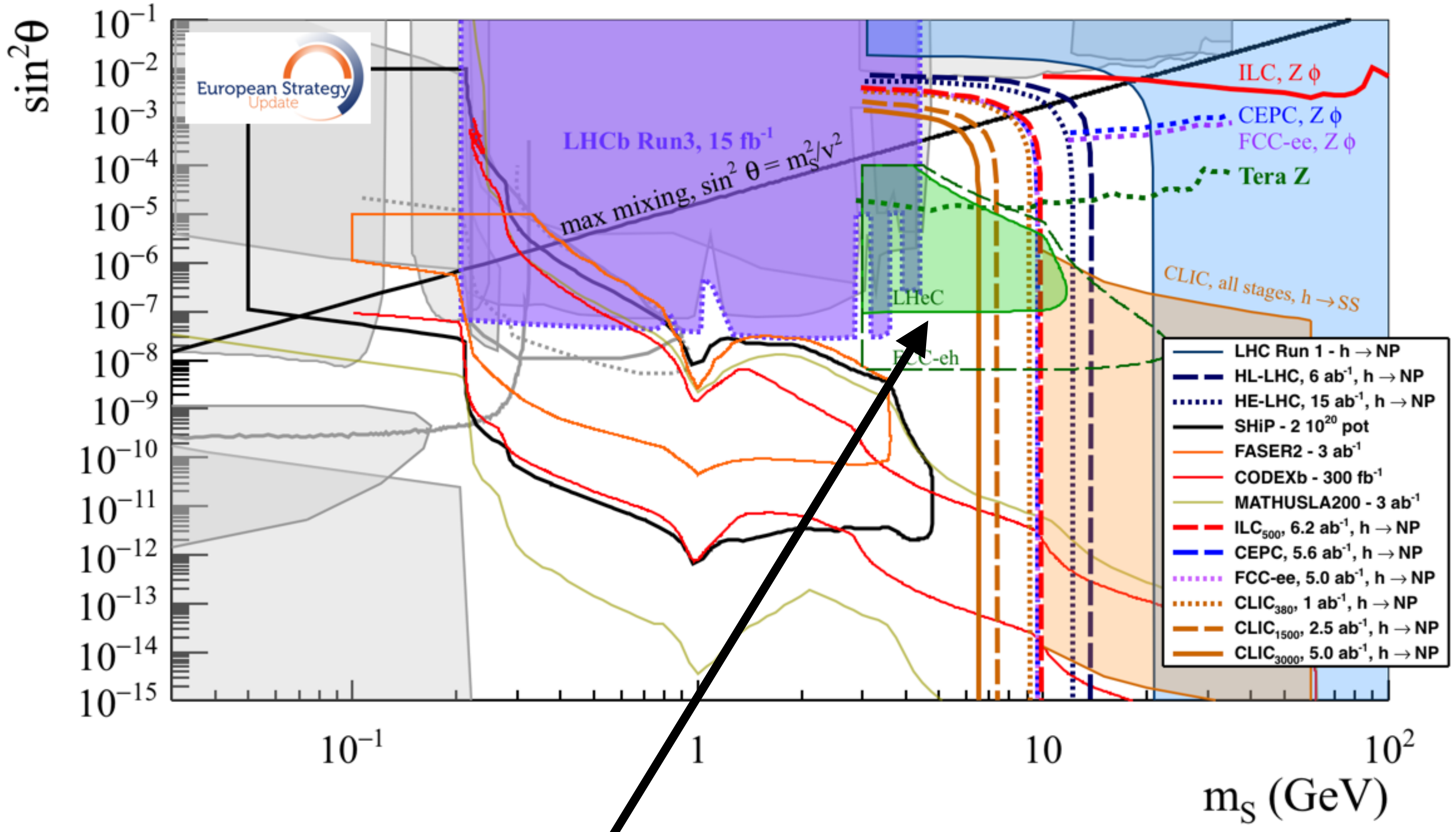
BSM physics: new scalars from Higgs

- New exotic scalars (X) from Higgs decay: displaced signatures if long-lived.
- X → 2+ charged particles above p_T threshold to identify DV and $r>r_{min}$ from PV: LLP.



Improvements wrt HL-LHC

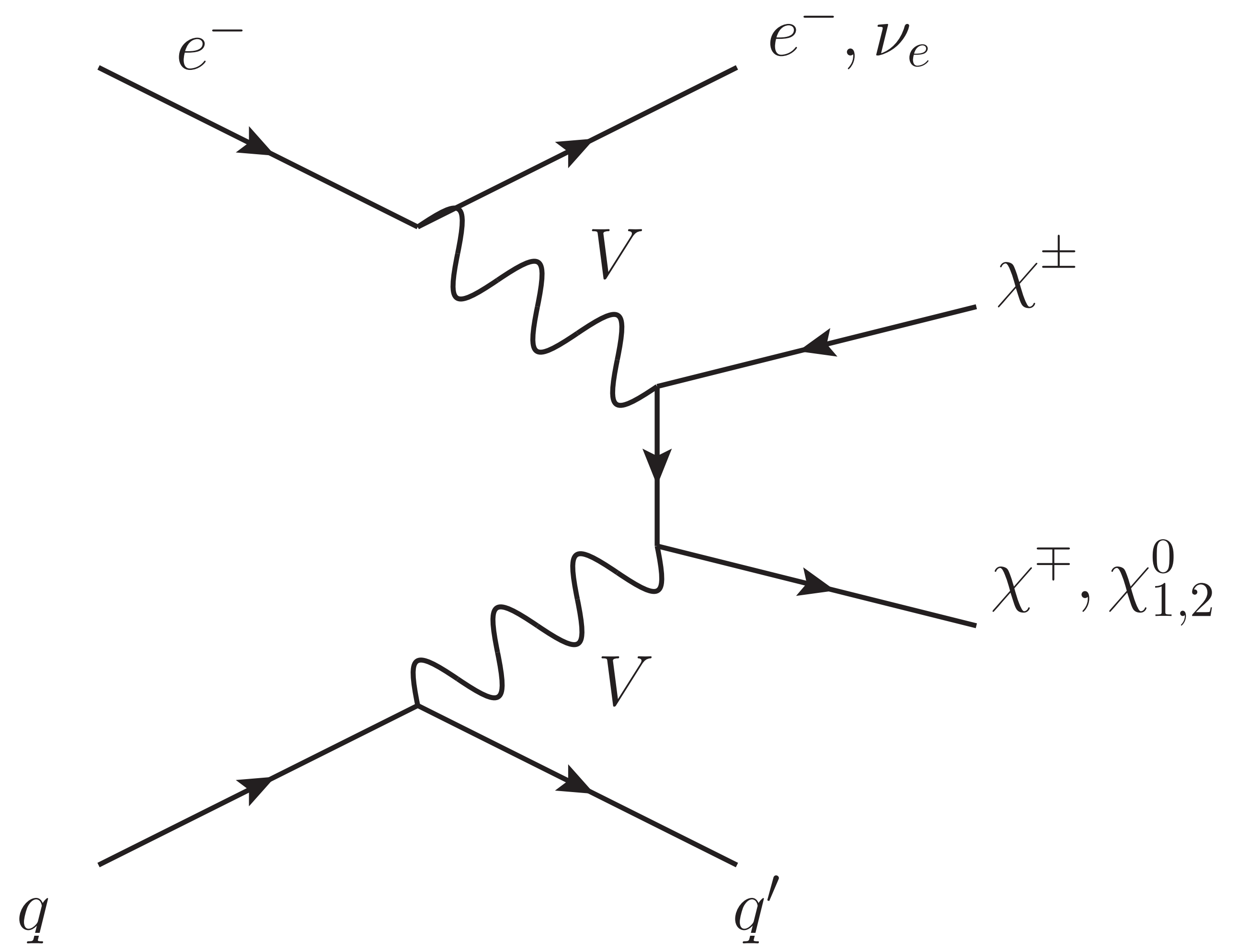


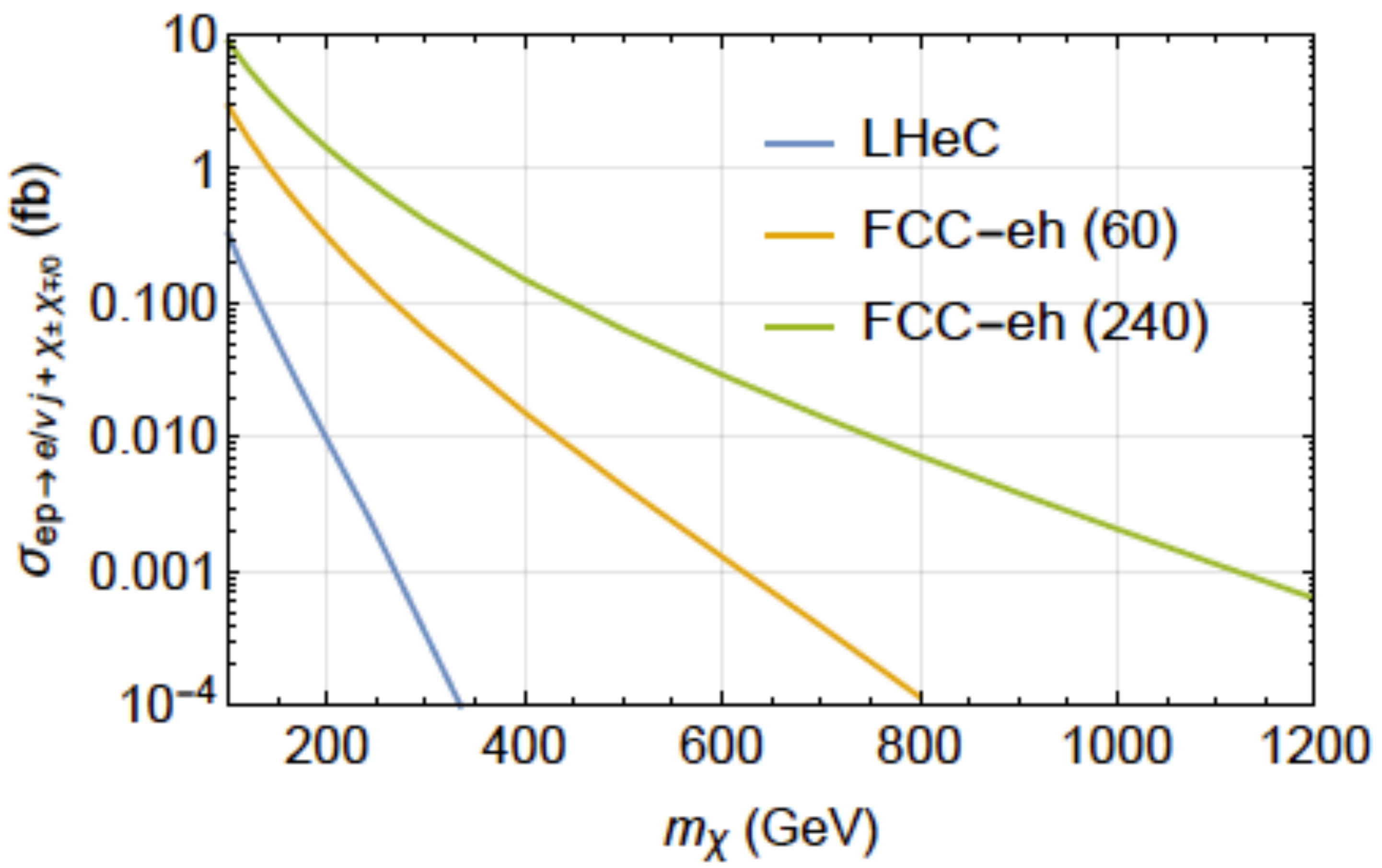


Covering regions between pp and e^+e^- / low energy experiments

BSM physics: disappearing tracks

- Searches for Higgsinos with masses O(100) GeV appearing in natural SUSY theories, through disappearing tracks.





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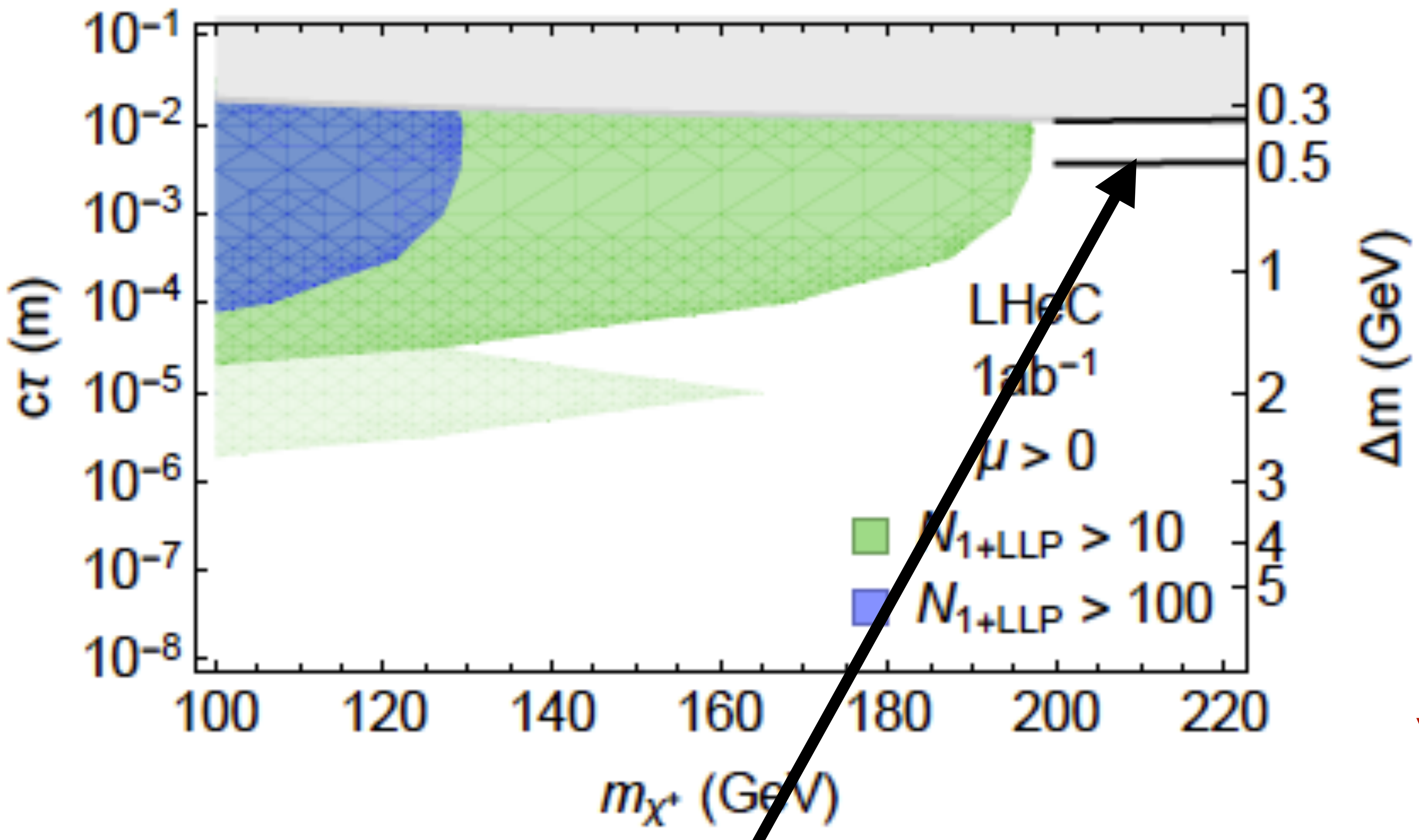
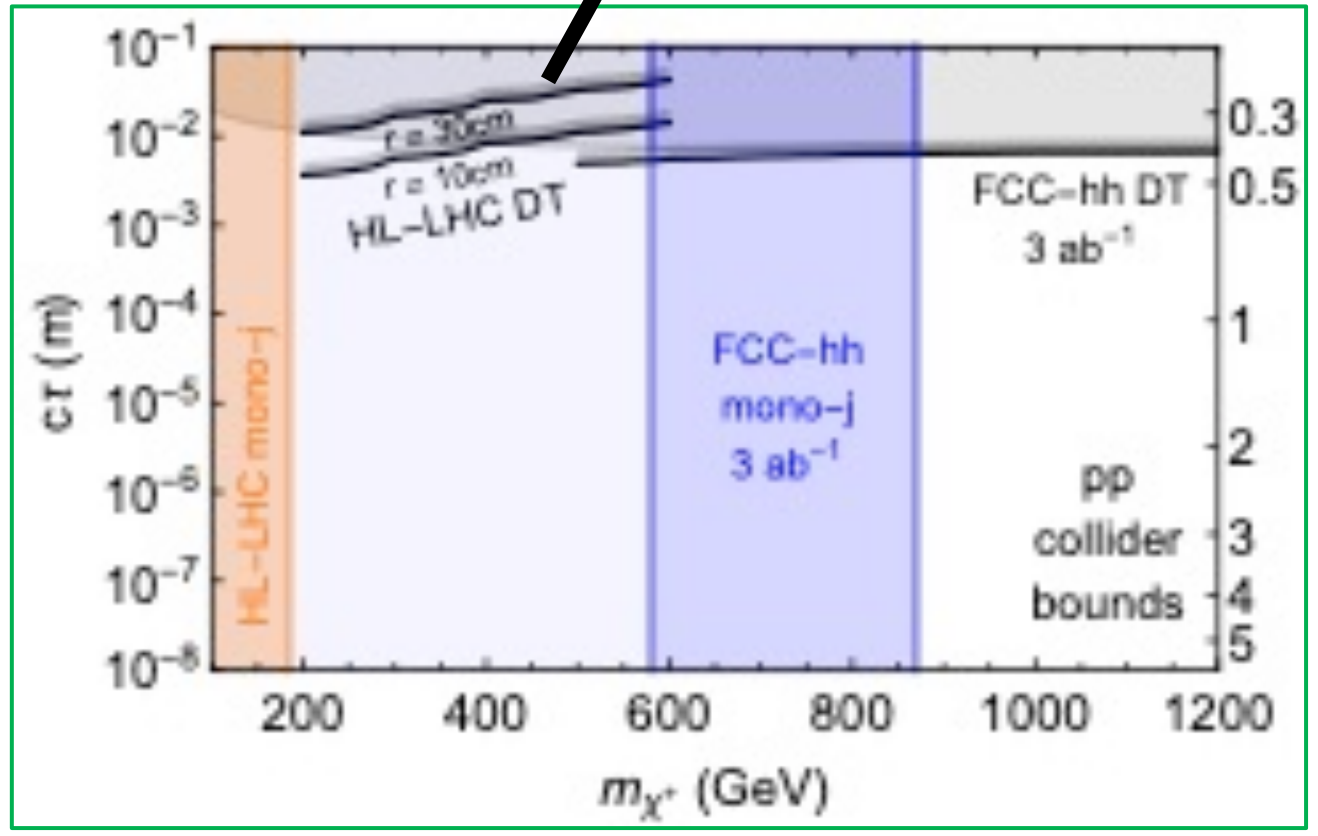




green (blue) region: 2σ sensitivity estimate in the presence of τ backgrounds; 10 (100) events with LLP observed.

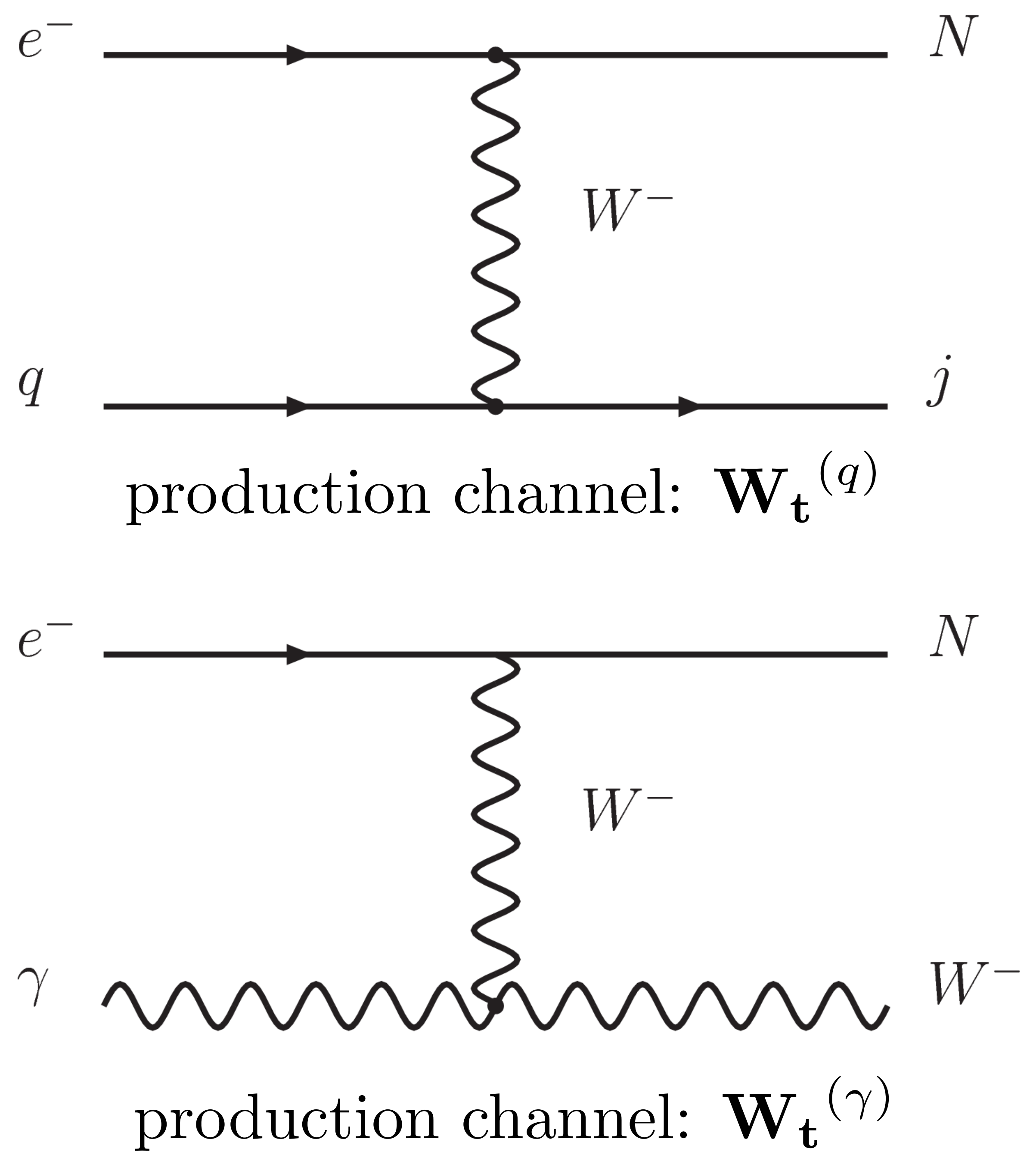
- Larger sensitivity to very short lifetimes than pp colliders.

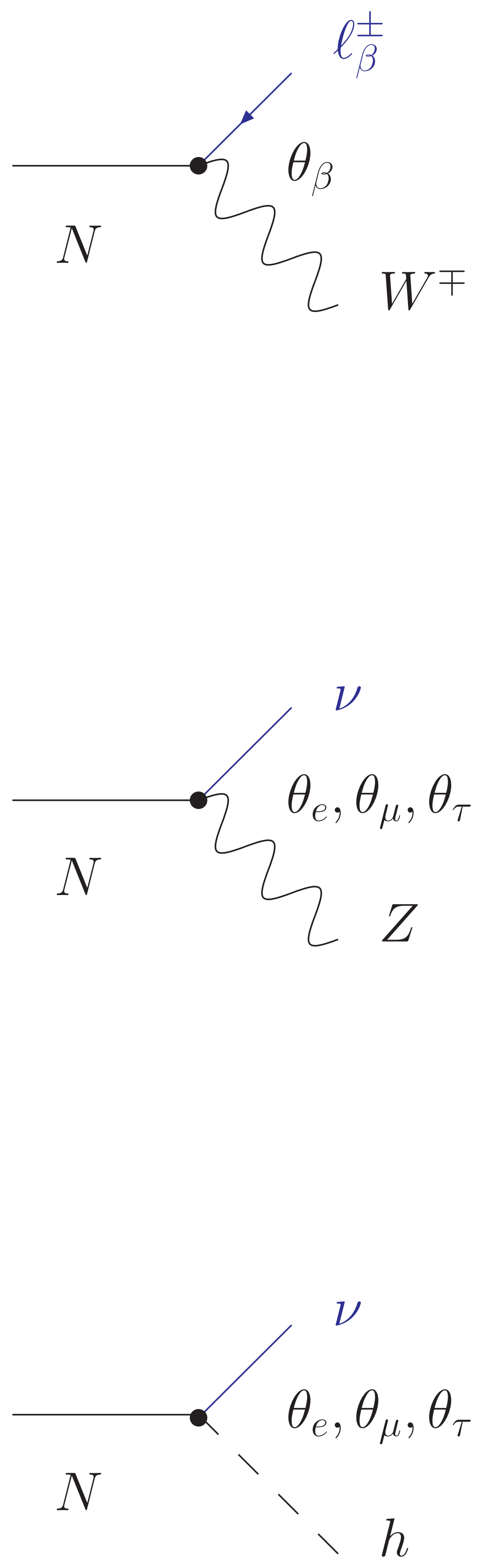
black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

BSM physics: heavy neutrinos

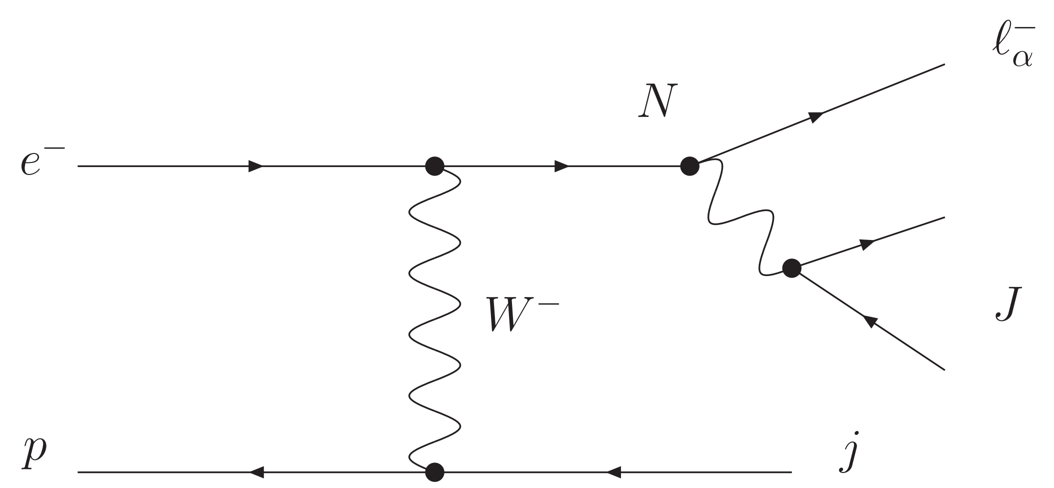
- In general, weakly produced and/or non-promptly decaying particles very challenging at pp and e^+e^- colliders: good complementarity with ep colliders, similarly to the case of the Higgs exotics decays, sterile neutrinos.

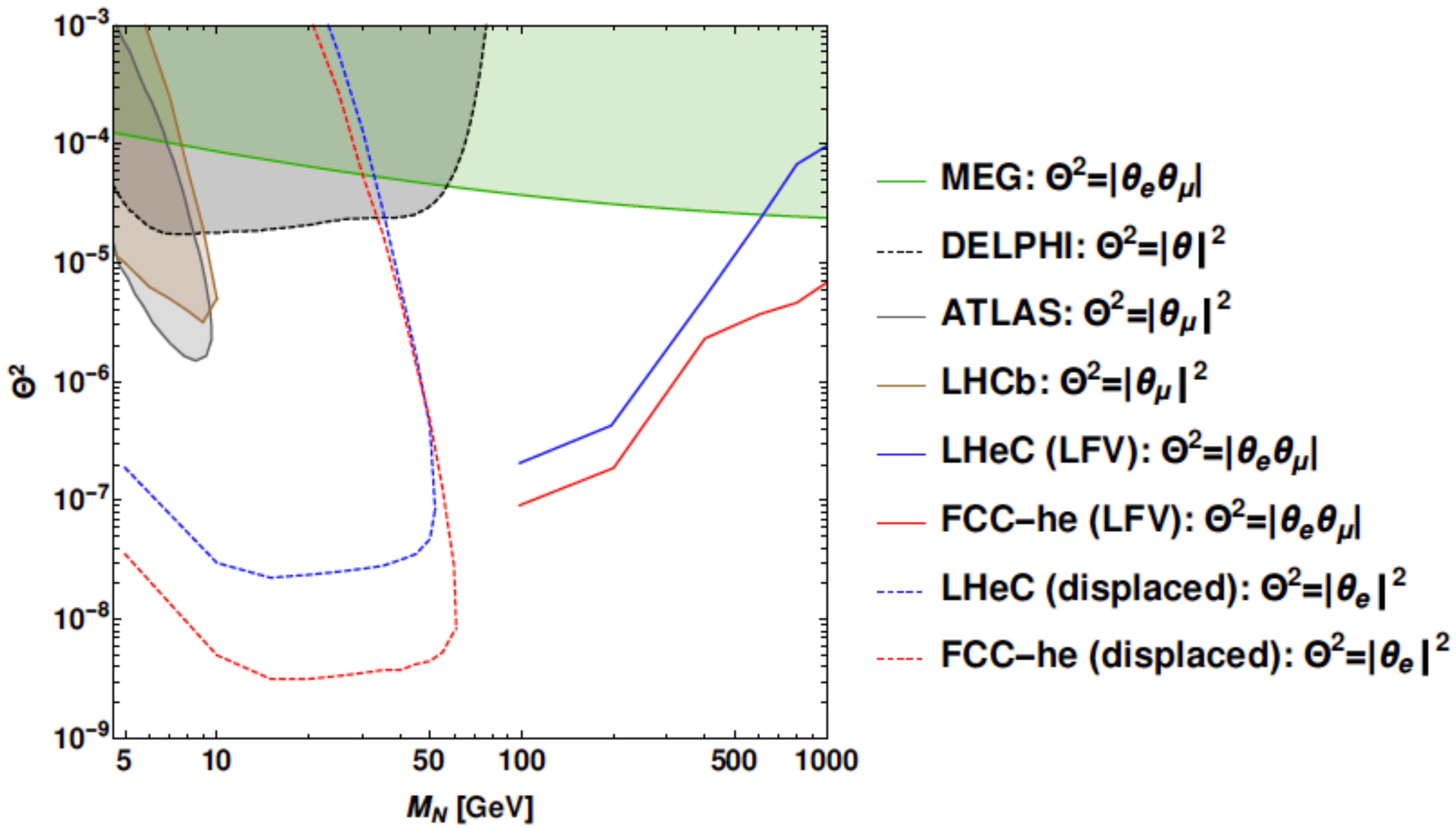
active-sterile neutrino mixing with the electron flavour → $|\theta_e|^2$





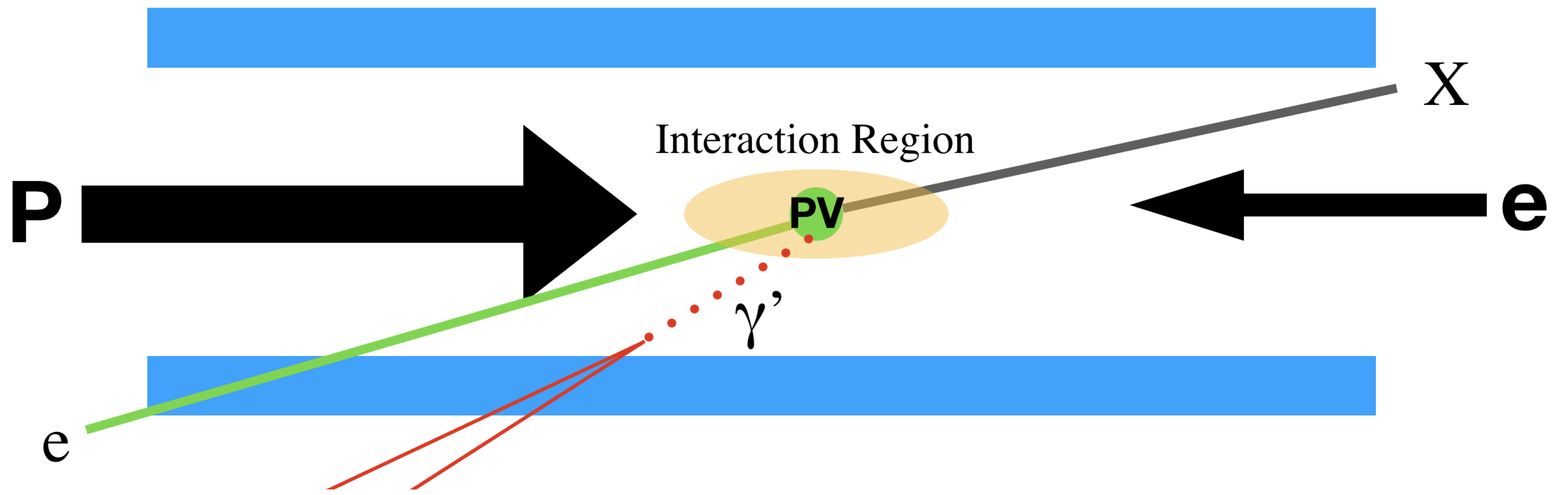
Sensitivity of the LFV lepton-trijet searches (at 95 % C.L.) and of the DV one

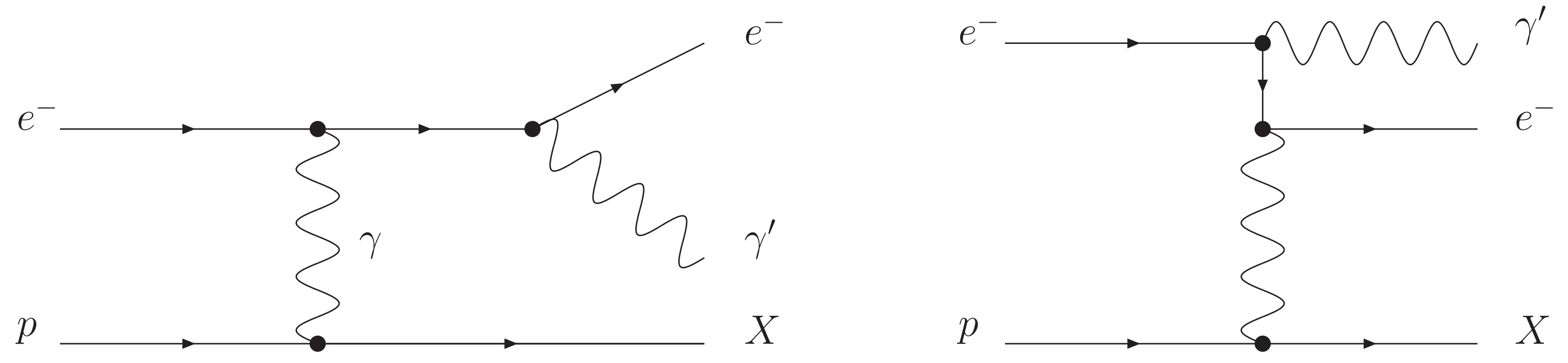


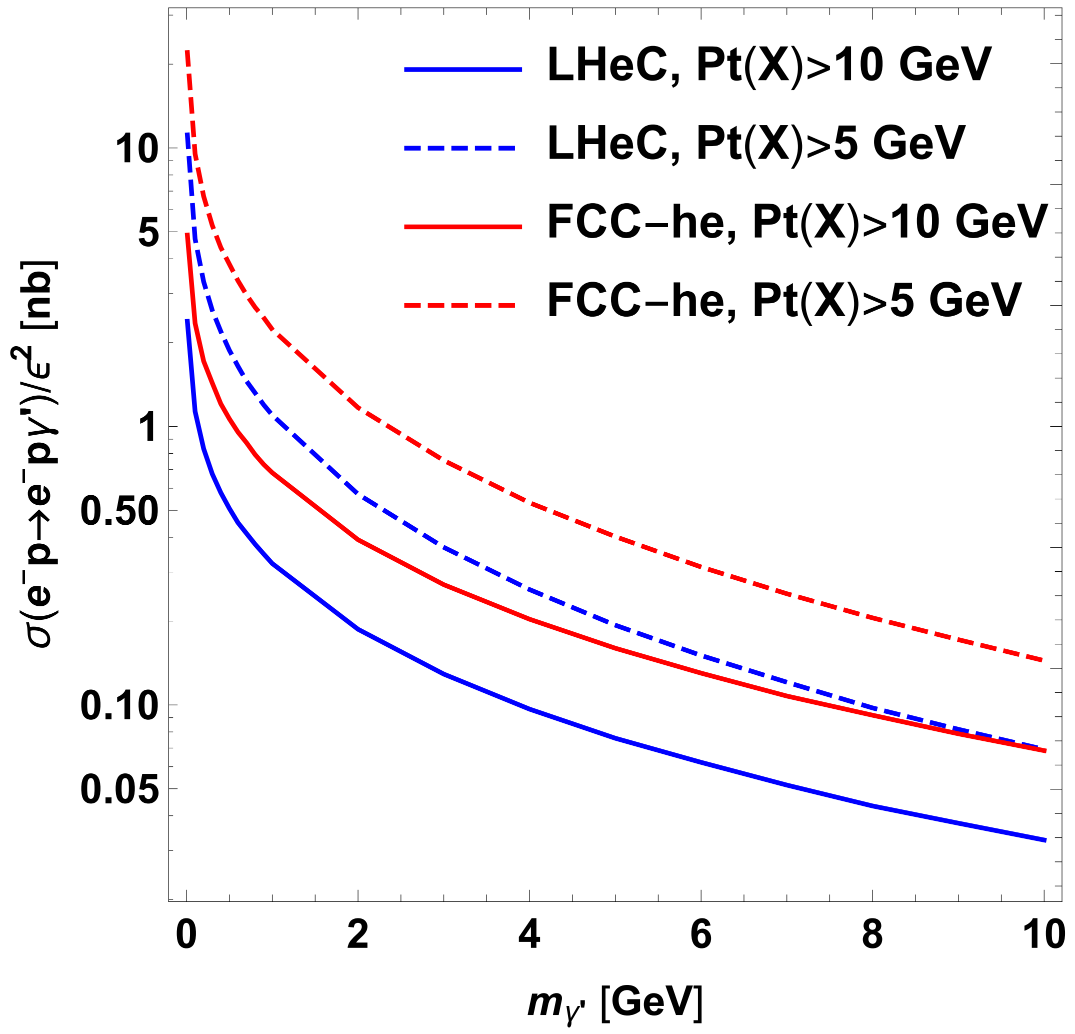


BSM physics: dark photons

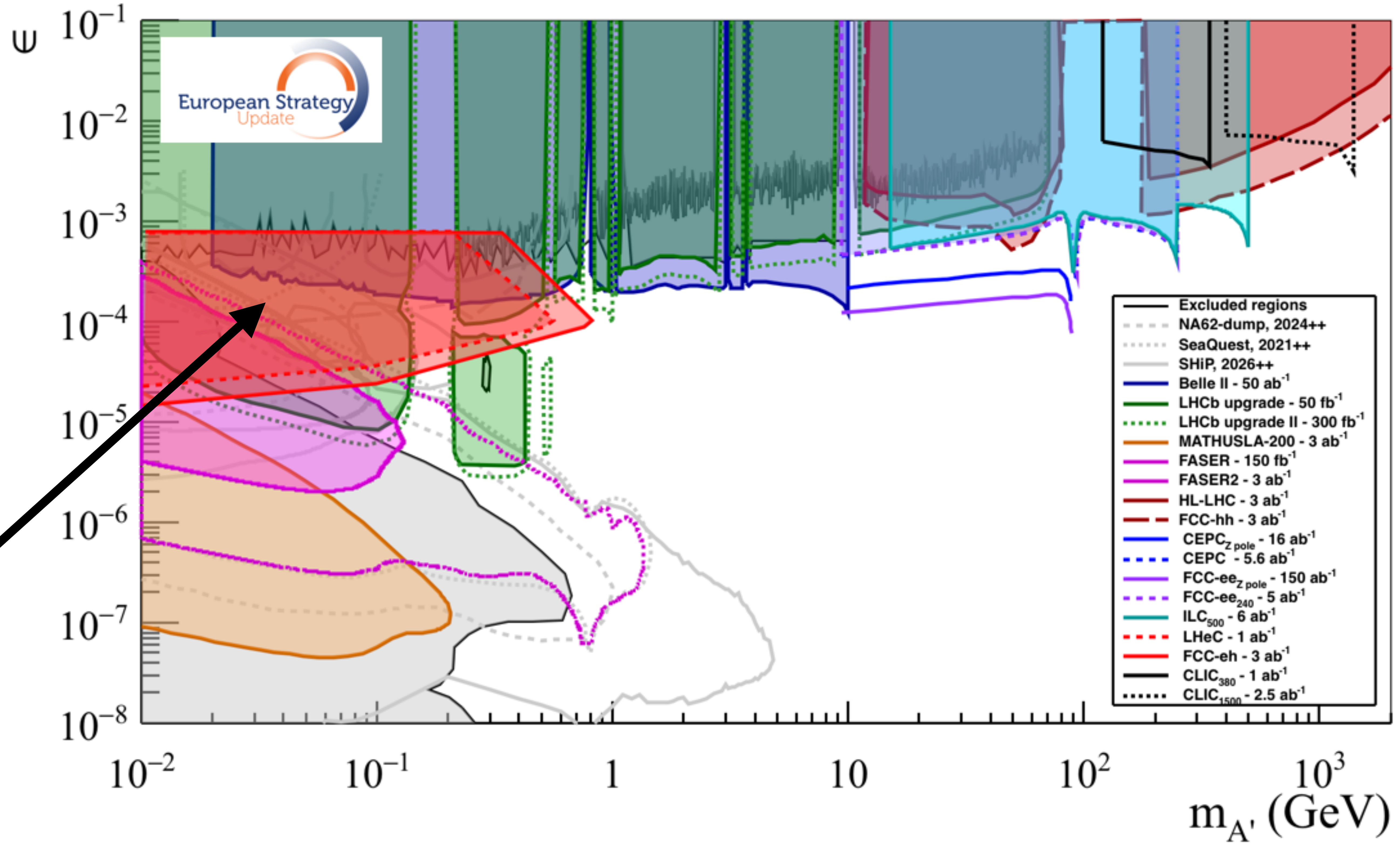
- Additional gauge boson mixed with the $U(1)_Y$ SM factor kinetically.
- Masses O(1) GeV, QED-like interactions, small mixing ε.
- Decay to pairs of leptons, hadrons, or quarks, which can give rise to a displaced vertex.







$$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$



Covering regions between pp and e⁺e⁻ / low energy experiments

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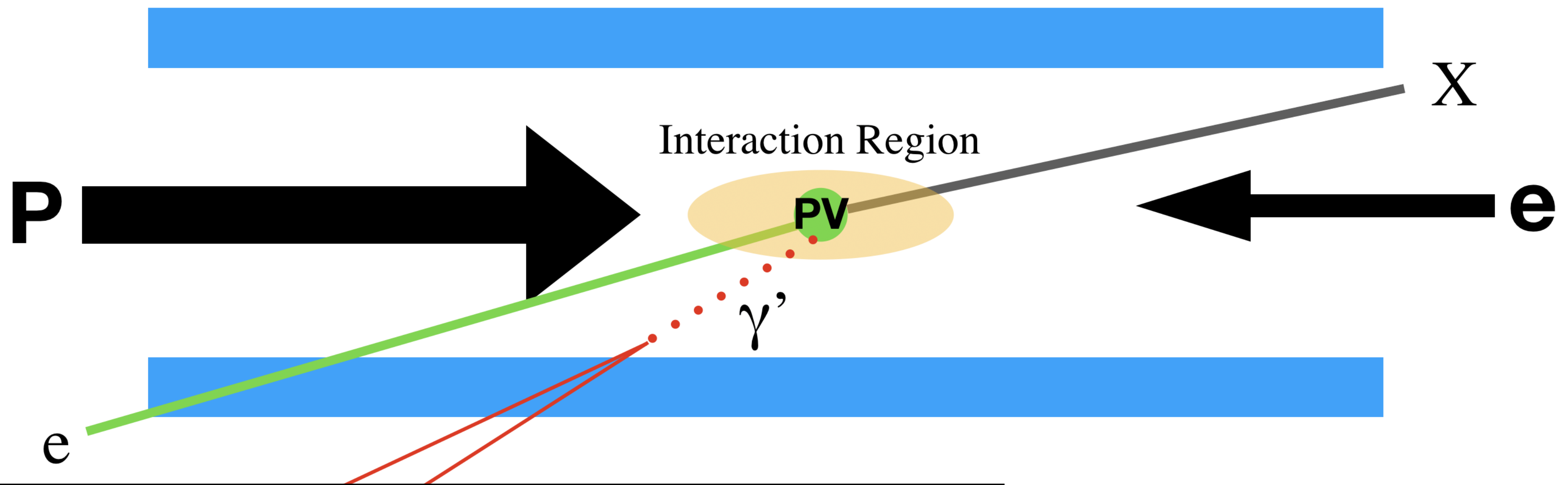
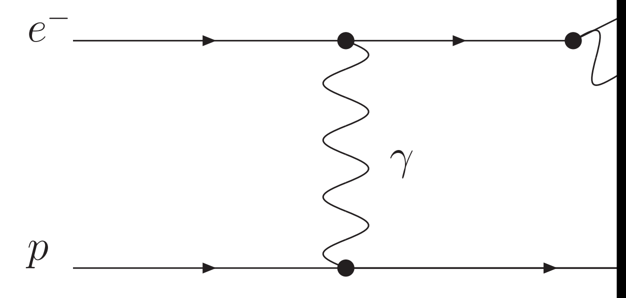
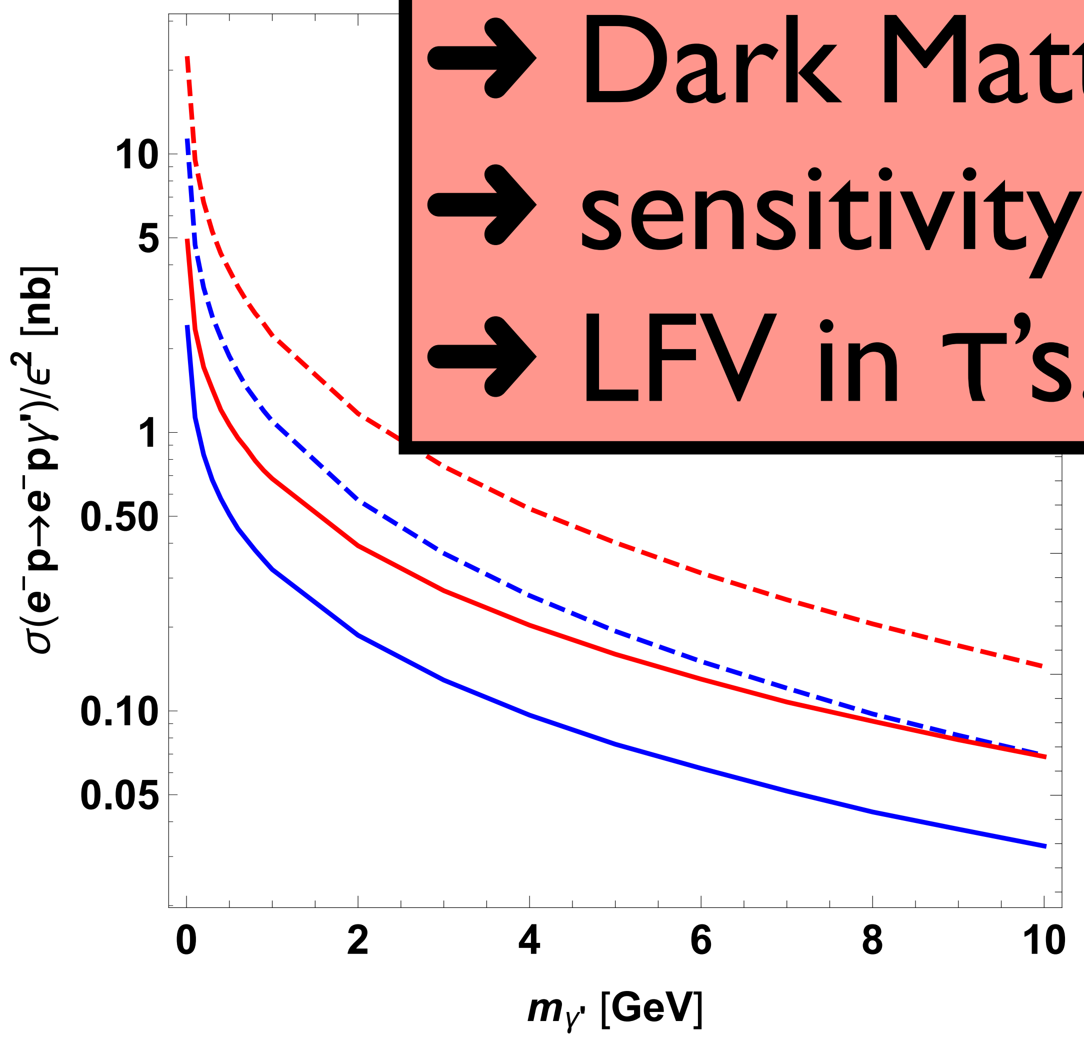


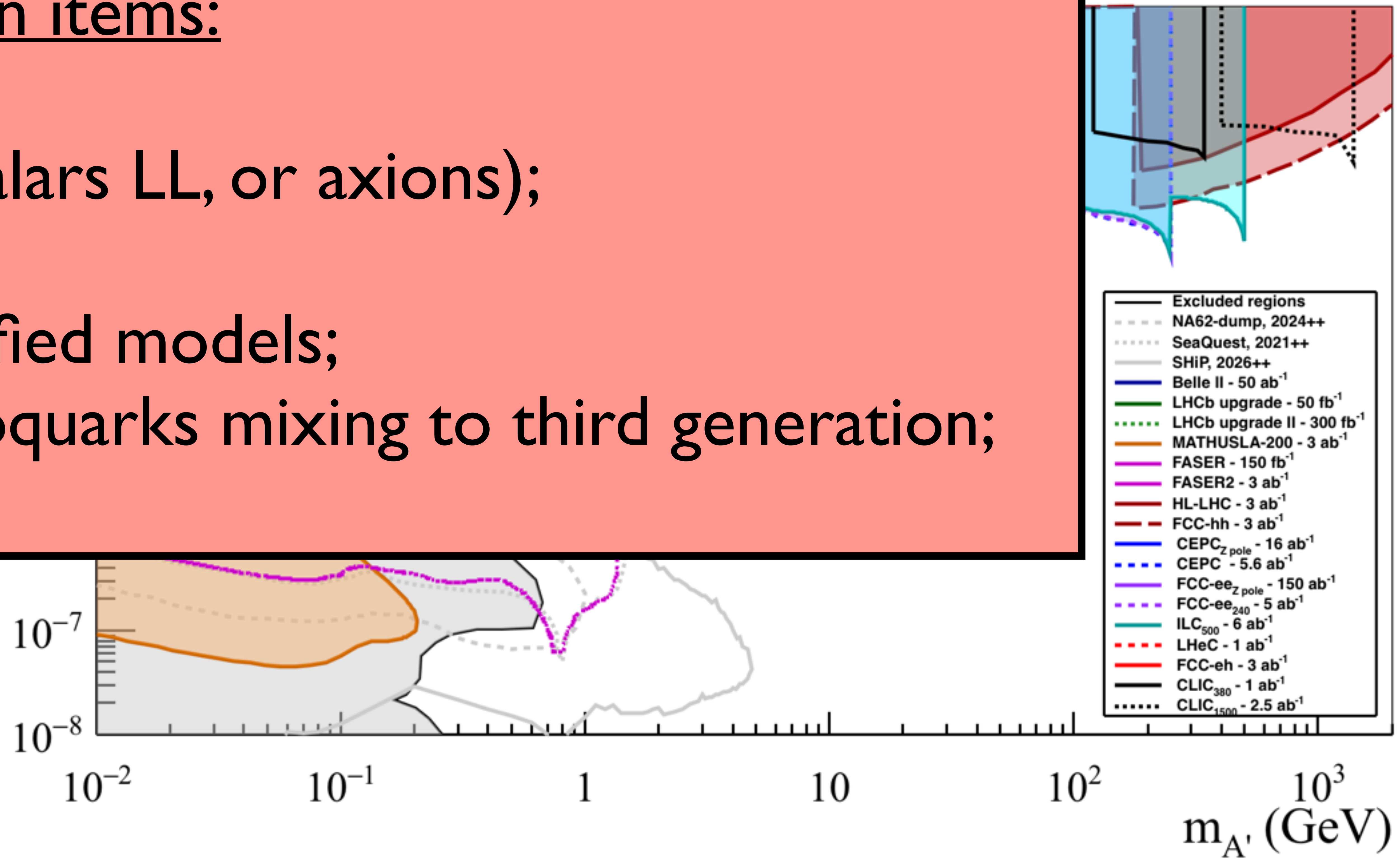




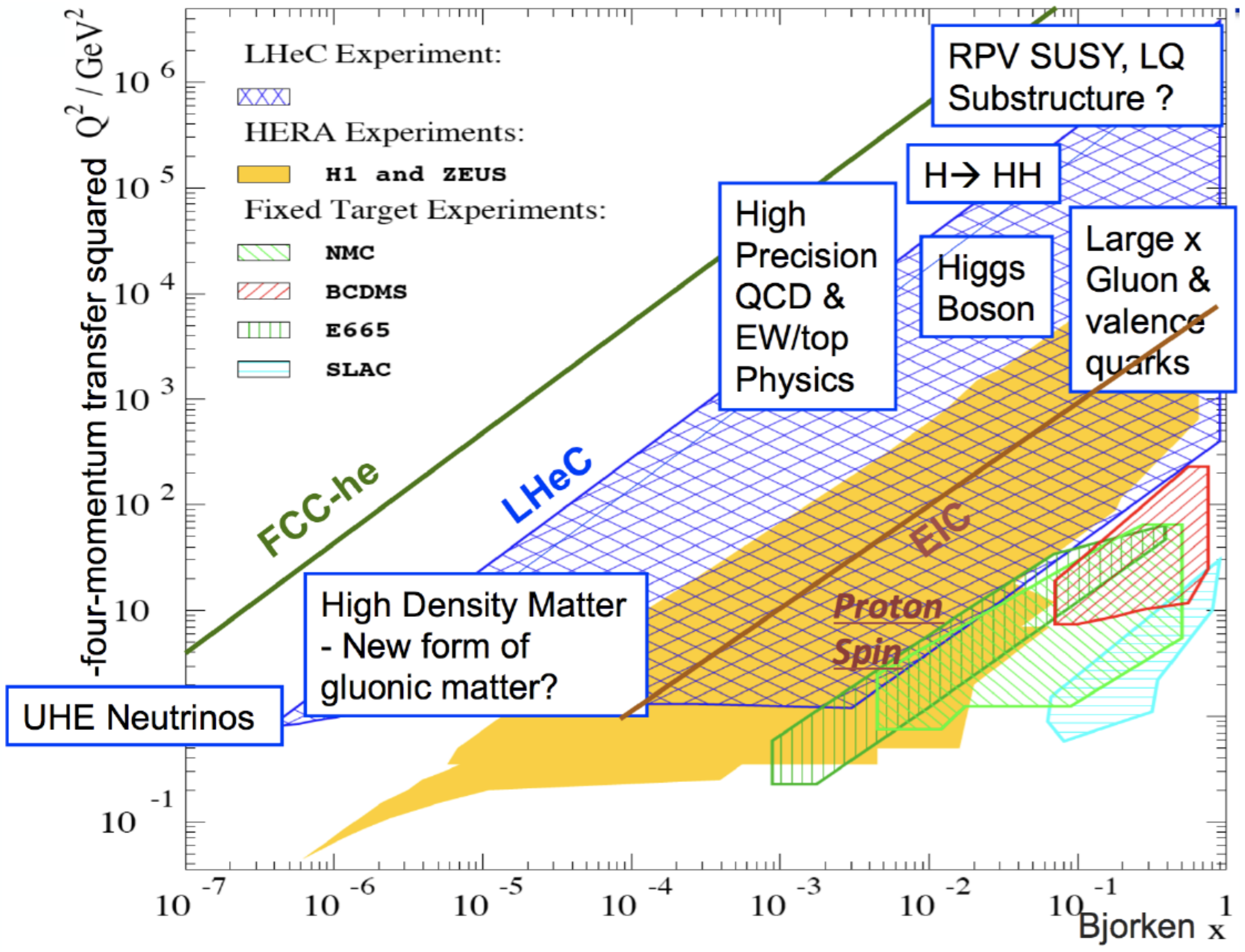
Open items:

➜ Exotics Higgs decays (e.g. in scalars LL, or axions);
➜ compositeness;
➜ Dark Matter searches in simplified models;
➜ sensitivity for observing a leptoquarks mixing to third generation;
➜ LFV in τ's.

Covering regions between pp and e⁺e⁻ / low energy experiments



Summary:



- **LHeC and FCC-eh:**
  ➜ Have a physics case on their own: obviously QCD (both precision and discovery in ep and eA), but also EW, top, Higgs, BSM.
  ➜ Enlarge the reach of hadronic colliders into (higher) precision (PDFs, factorisation), both for pp and for AA.
  ➜ Have complementarities and synergies with the other collision modes: hh and e^+e^-.

- LHeC gives the possibility of new accelerator and detector development at CERN in the 2030's that sustains HL-LHC while preparing for colliders that cost $\mathcal{O}(10)$ BCHF.

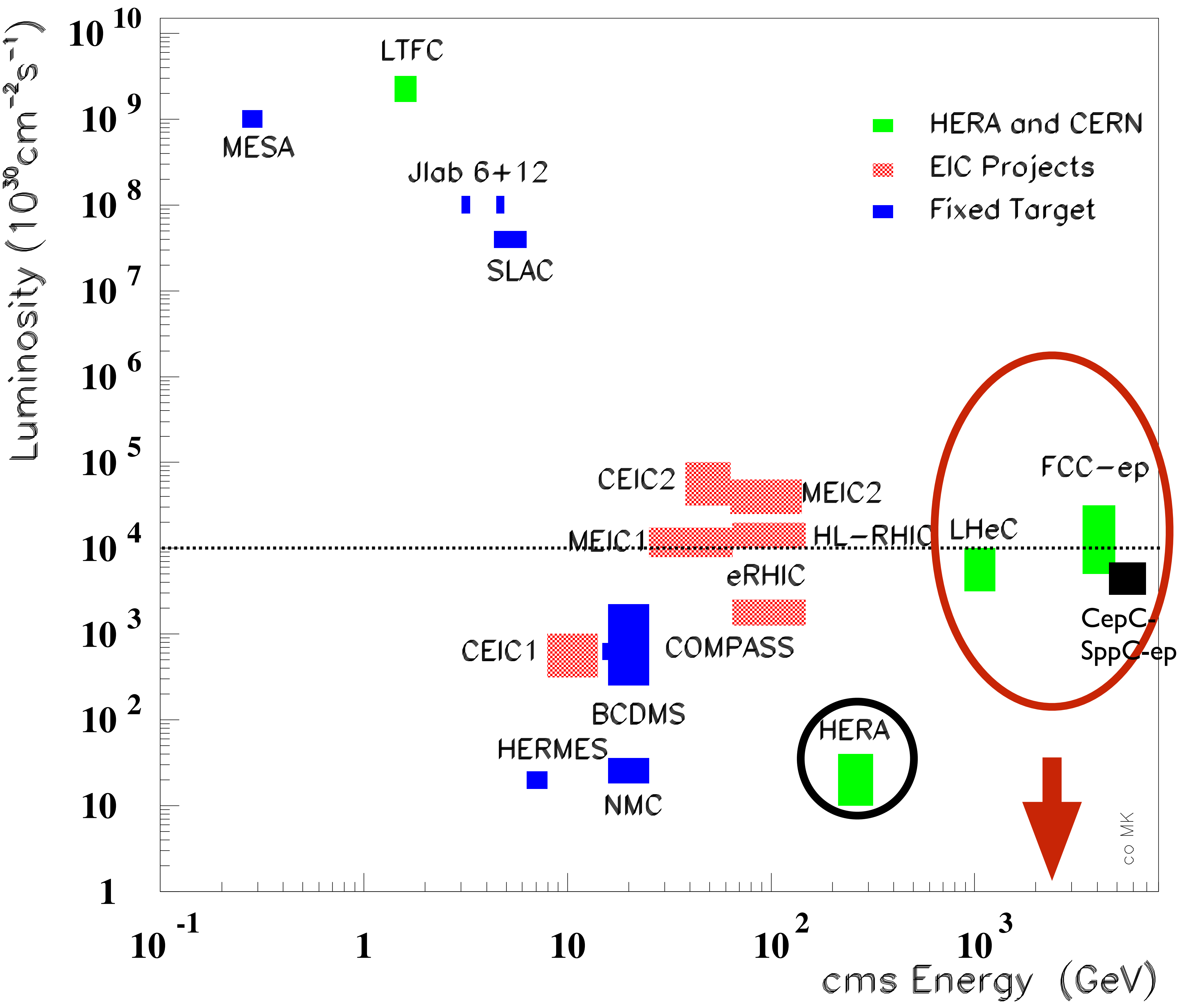
Open questions and further work to be done:

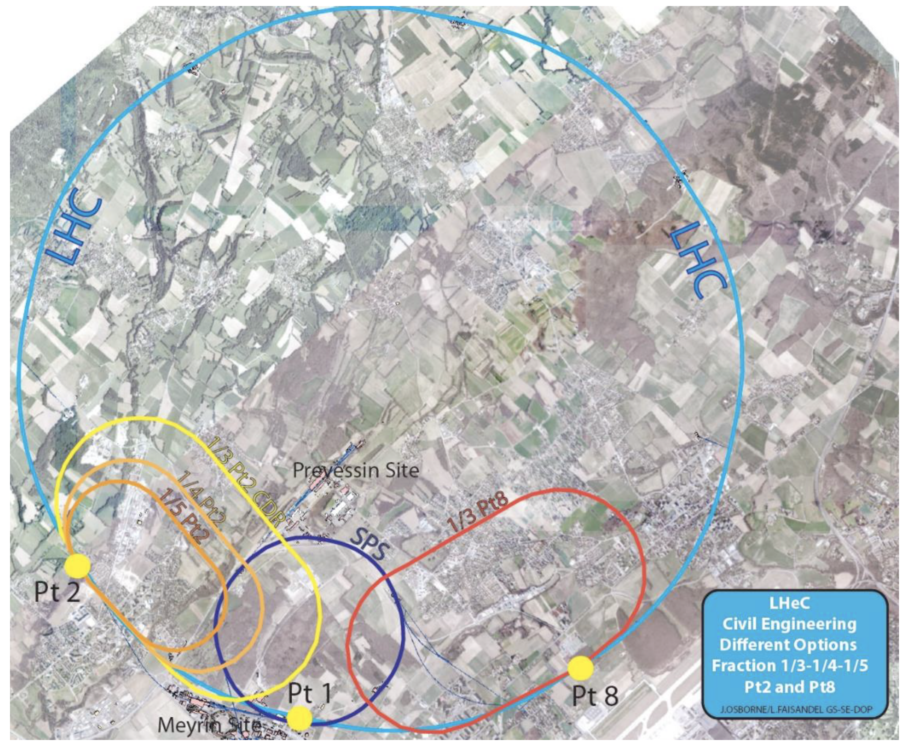
Topic	Open items & to be done
All	DIS MC for very high energies (ep and eA), including H, Z, W, top, photon in p, and radiative corrections; multi jet production; complementarity with hh; studies with full detector simulation (once IR is designed)
PDFs, α_s	N^3LO evolution and massive ME; NNLO for differential heavy quark production
Small-x dynamics, eA	Impact of resummation on hadronic observables other than Higgs; study on ability of LHeC/FCC-eh to discriminate between different small-x treatments, in both ep and eA
Higgs	Full HL-LHC+LHeC SMEFT analysis with EW input
EW	EW corrections in MSbar for comparing results; 2-loop EW corrections and beyond
BSM	Exotics Higgs decays (e.g. in scalars LL, or axions); compositeness; Dark Matter searches in simplified models; LFV in taus; LQs mixing to third generation

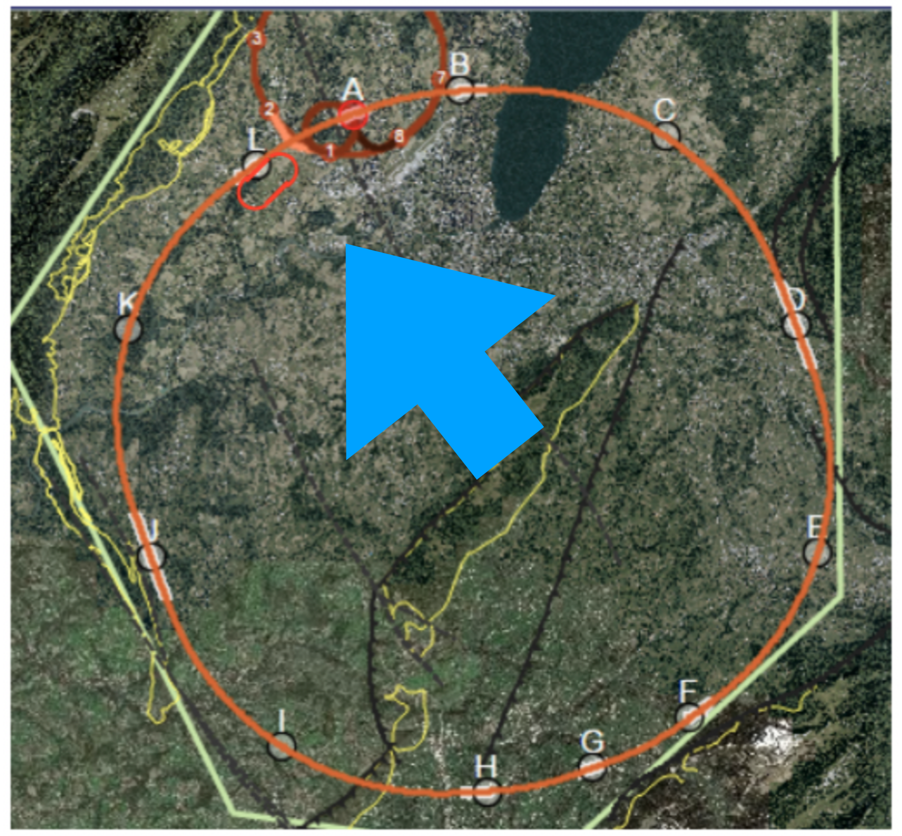
Backup:

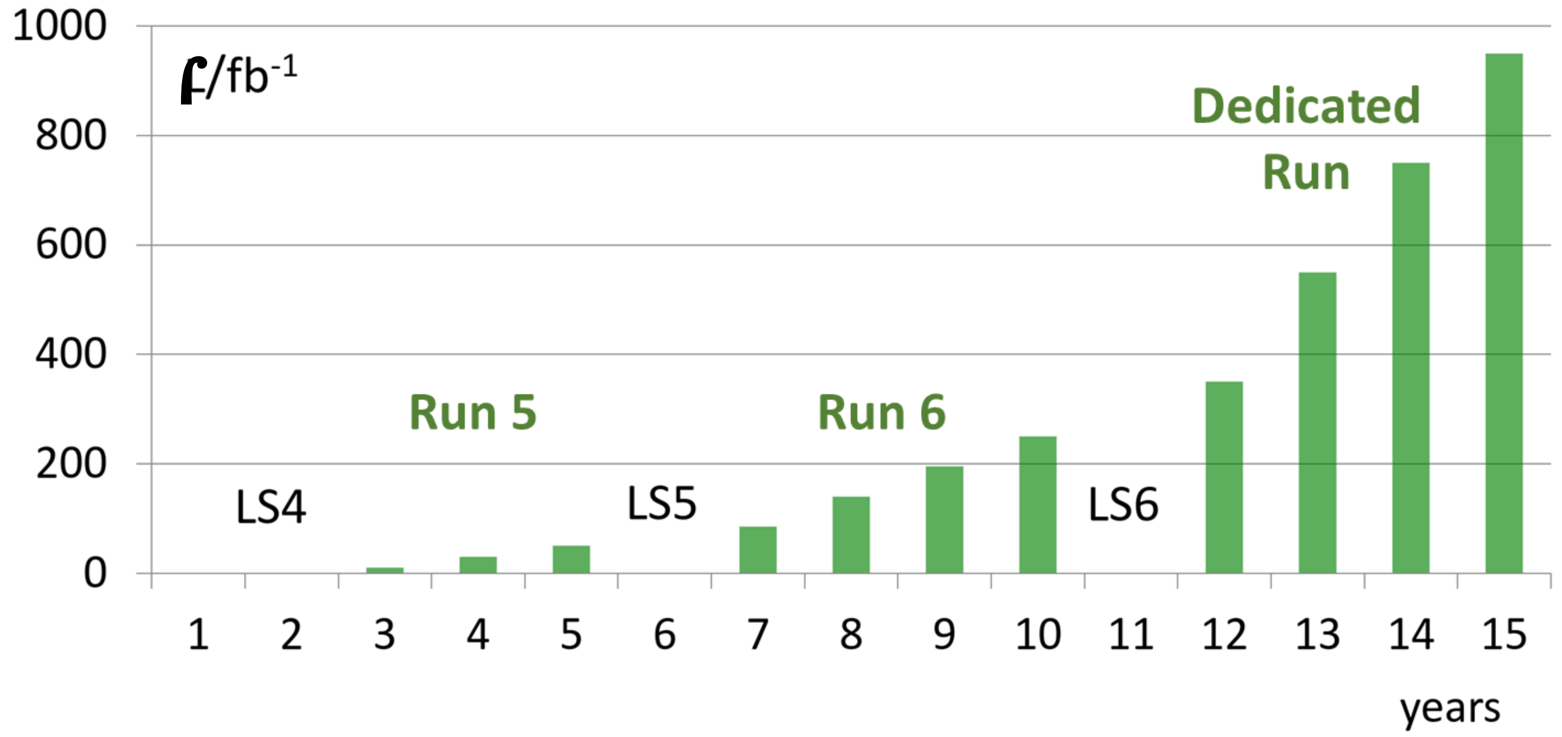
Accelerators:

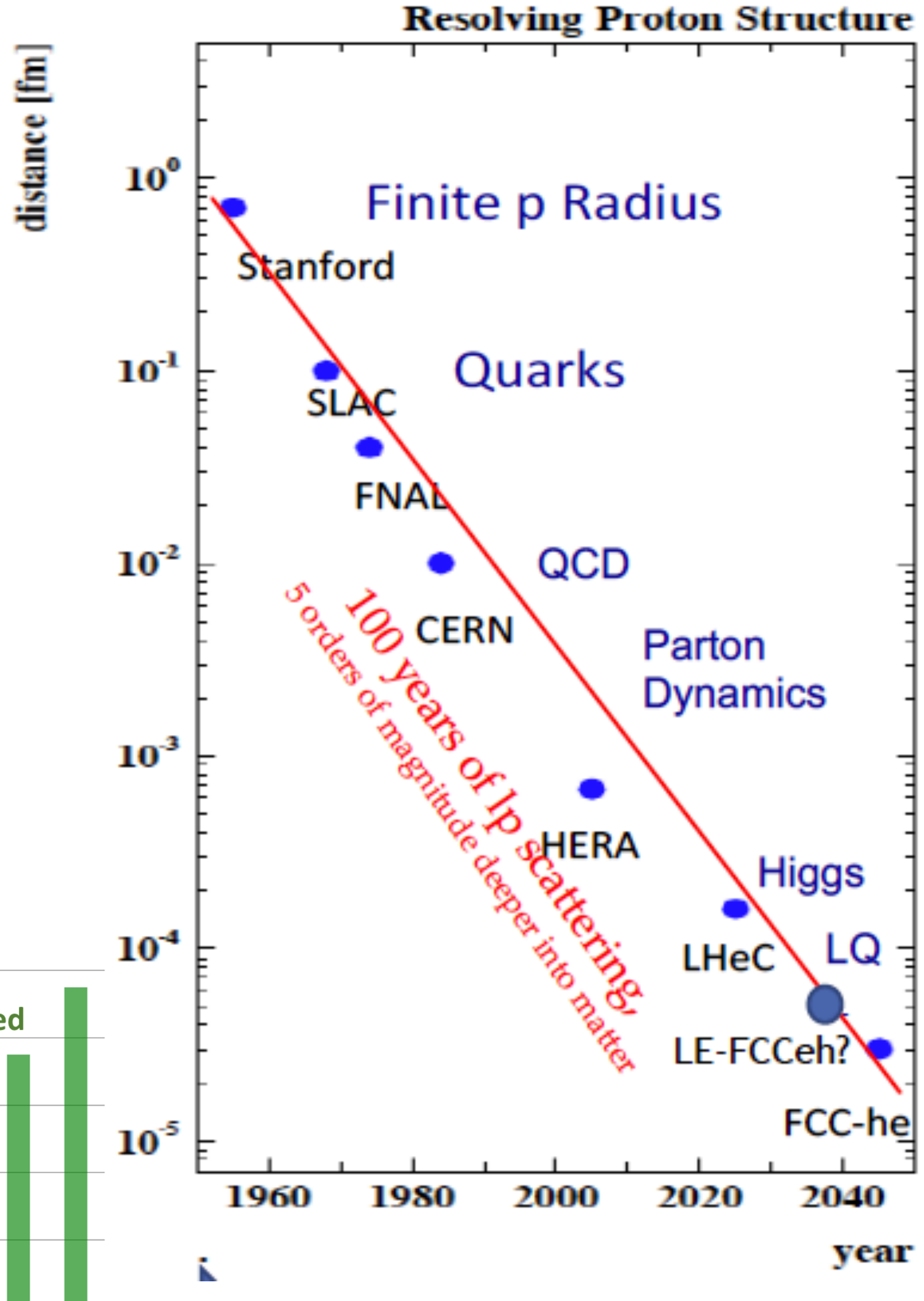
Lepton-proton/nucleus scattering facilities









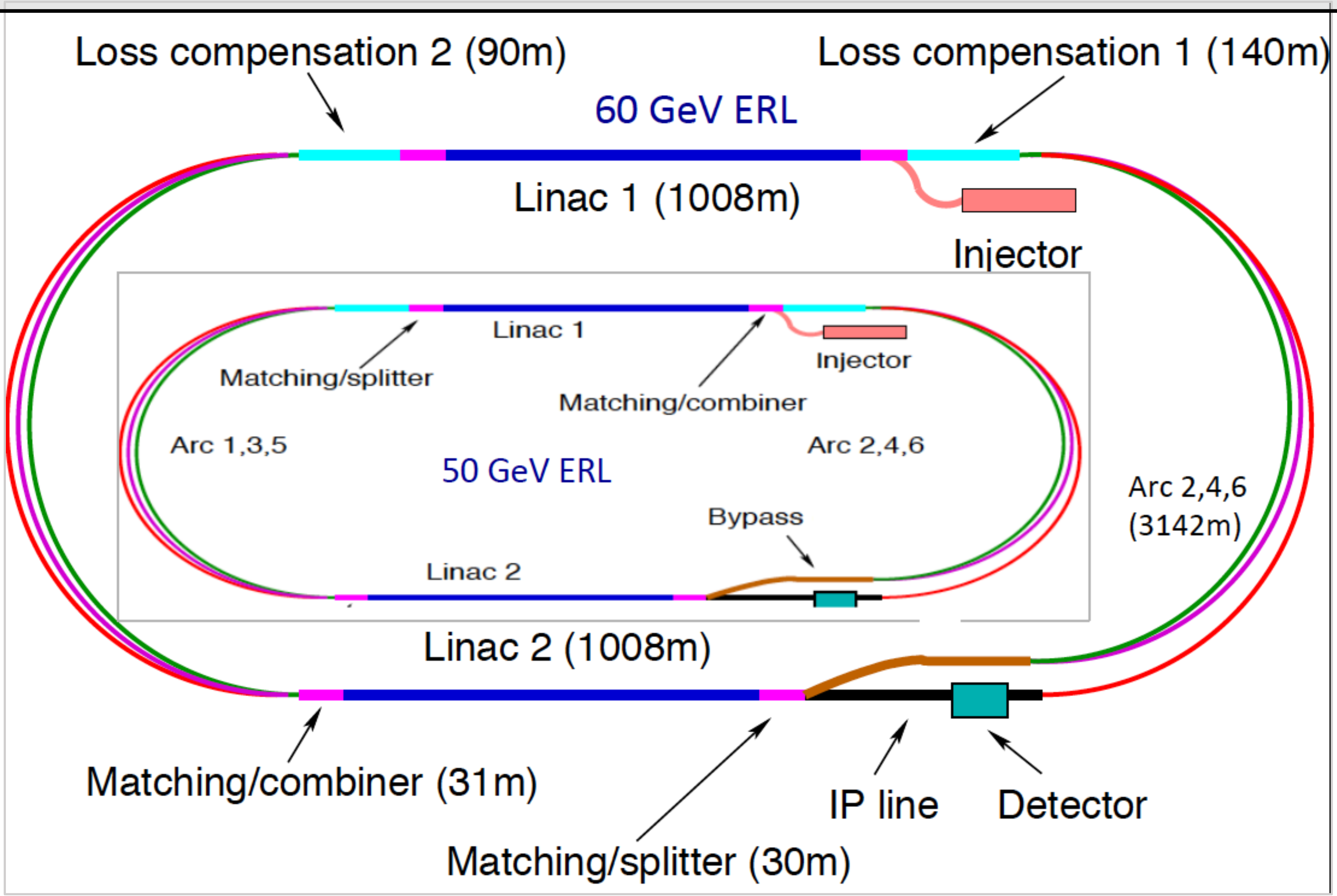


Luminosities: ~10^{34} (10^{33}) cm^{-2}s^{-1} in ep (ePb) (details in backup).

ERL:

- Constraints on ep:
  - ➜ Synchronous with pp.
  - ➜ No disruption on (HL-)LHC or FCC-hh working.
  - ➜ Power consumption < 100 MW (70 MW for accelerator).
  - ➜ High luminosity ~ 10^{34} cm^{-2}s^{-1} for Higgs studies.
  - ➜ E_e>50 GeV for Higgs, top and BSM studies.

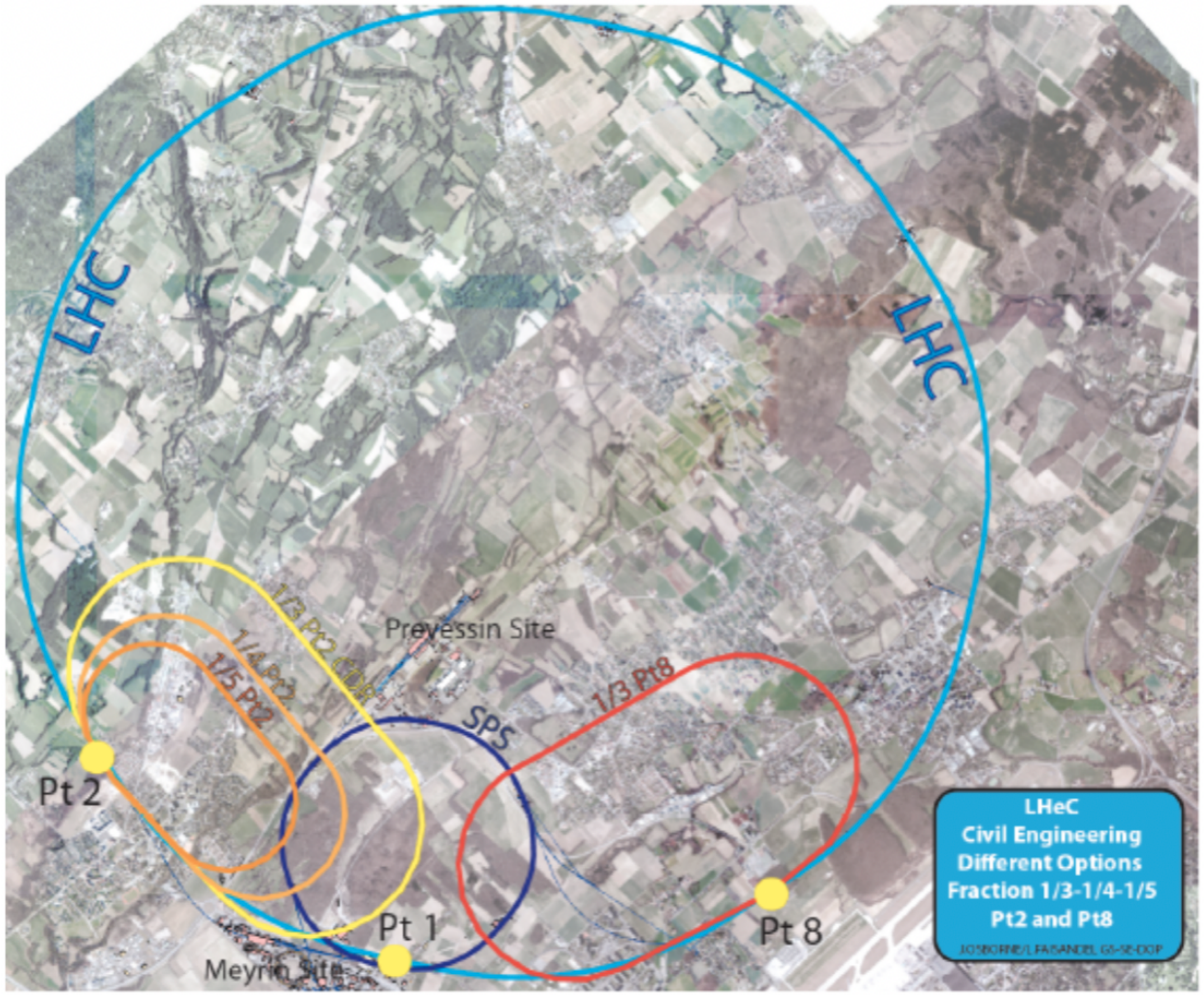
⇒ led to the **3-pass energy recovery racetrack.**

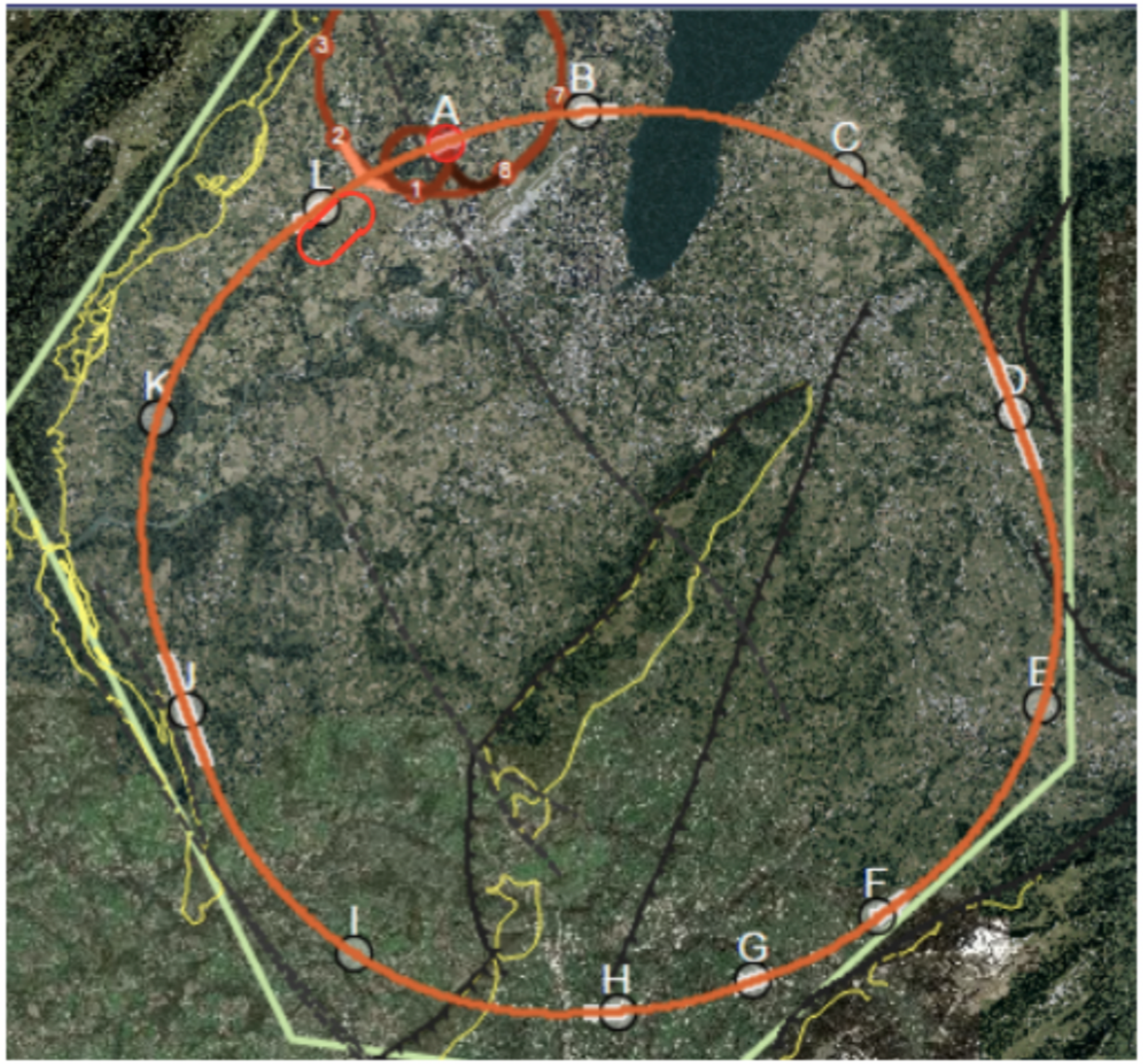


- Modular for HL-LHC and FCC-hh.
- Injector for FCC-ee?
- γp/γγ collider?

- ERL for electron cooling at EIC.
- PERLE@Orasay: demonstrator.

Footprint:

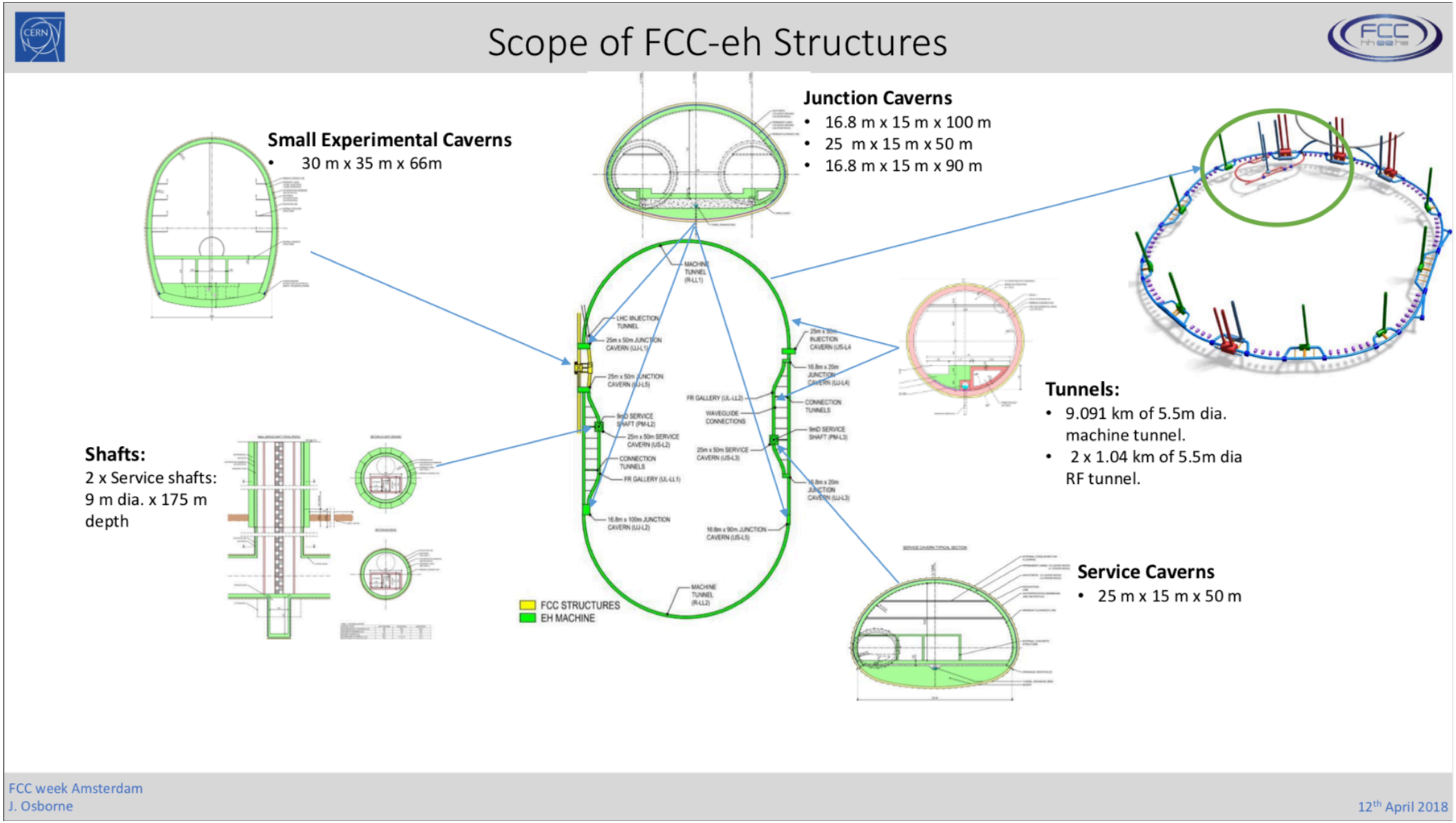




- IP2 as preferred location: larger cavern, smaller/simpler infrastructure required, ALICE finishes in LS4 (but new experiment proposed?).

- Points A and G for the GPDs, present option for ep seems to be point L.

Footprint:



Scope of FCC-eh Structures
Small Experimental Caverns
• 30 m x 35 m x 66m
Junction Caverns
• 16.8 m x 15 m x 100 m
• 25 m x 15 m x 50 m
• 16.8 m x 15 m x 90 m
Tunnels:
• 9.091 km of 5.5m dia. machine tunnel.
• 2 x 1.04 km of 5.5m dia RF tunnel.
Shafts:
2 x Service shafts: 9 m dia. x 175 m depth
Service Caverns
• 25 m x 15 m x 50 m
FCC STRUCTURES
EH MACHINE
FCC week Amsterdam
J. Osborne
12th April 2018

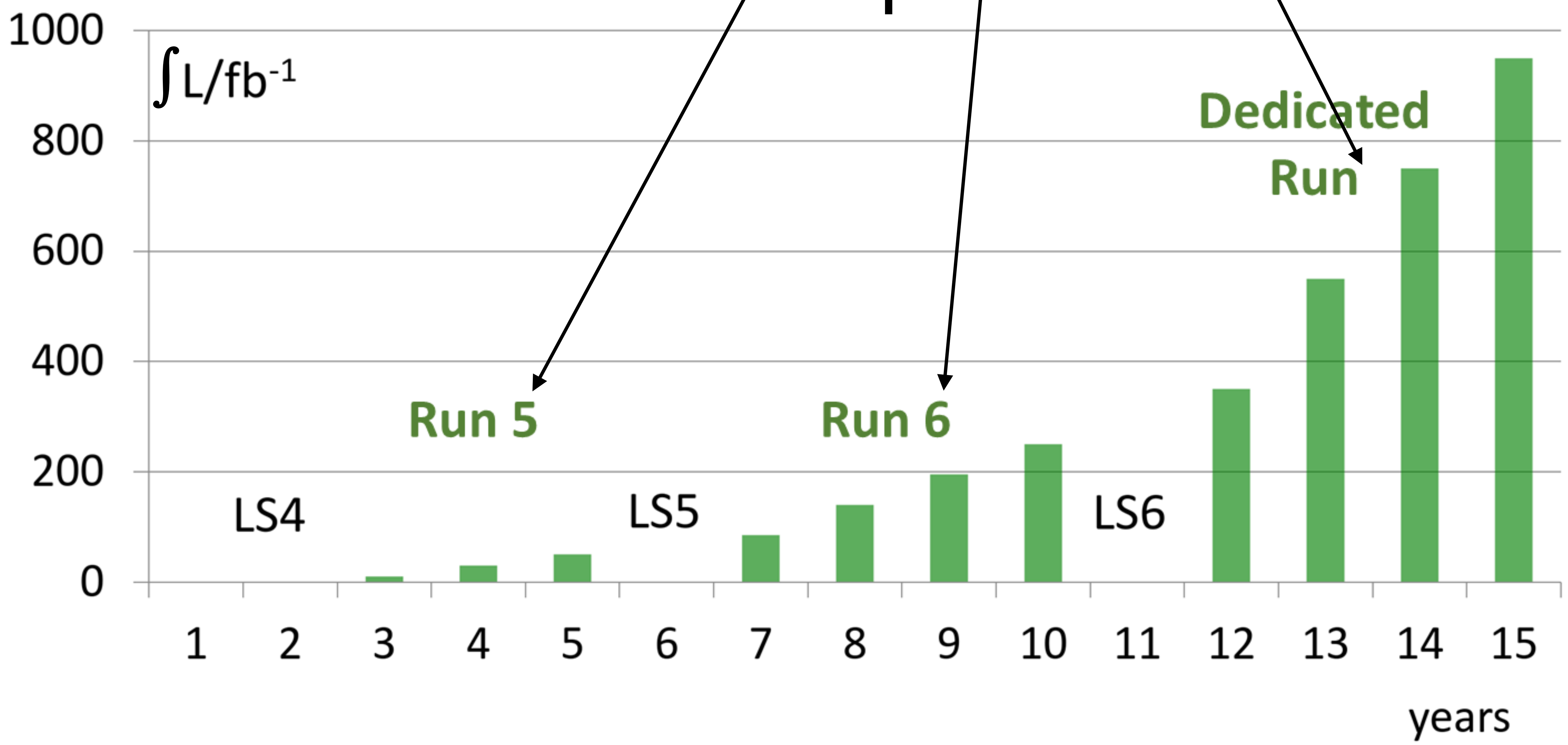
Luminosities:

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15

ePb

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β^*_A	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

ep



- P=±0.8 (electrons): important for Higgs, not used in BSM.
- Positrons: P=0, ~1/1000 luminosity.
- FCC-eh could deliver ~2 ab^{-1}.
- ePb integrated luminosities can be estimated 1/100 those in ep (10 times smaller luminosity times 10 times smaller running time).

Components and cost:

Section	Horizontal Dipoles			Vertical Dipoles			Quadrupoles			RF Cavities		
	Number	*Field*	*Mag. Length*	*Number*	*Field*	*Mag. Length*	*Number*	*Gradient*	*Mag. Length*	*Number*	*Frequency/Cell*	*RF Gradient*
LINAC 1							29	1.9	1.0	448	802/5	20.0
LINAC 2							29	1.9	1.0	448	802/5	20.0
Arc 1	344	0.039	4.0	8	0.51	4.0	158	9.3	1.0			
Arc 2	294	0.077	4.0	6	0.74	4.0	138	17.7	1.0			
Arc 3	344	0.123	4.0	6	0.92	4.0	158	24.3	1.0	6	1604/9	30.0
Arc 4	294	0.181	4.0	6	1.23	4.0	138	27.2	1.0	6	1604/9	30.0
Arc 5	344	0.189	4.0	4	0.77	4.0	156	33.9	1.0	18	1604/9	30.0
Arc 6	344	0.226	4.0	4	1.49	4.0	156	40.8	1.0	30	1604/9	30.0
Total	**1964**			**34**			**962**			**956**		

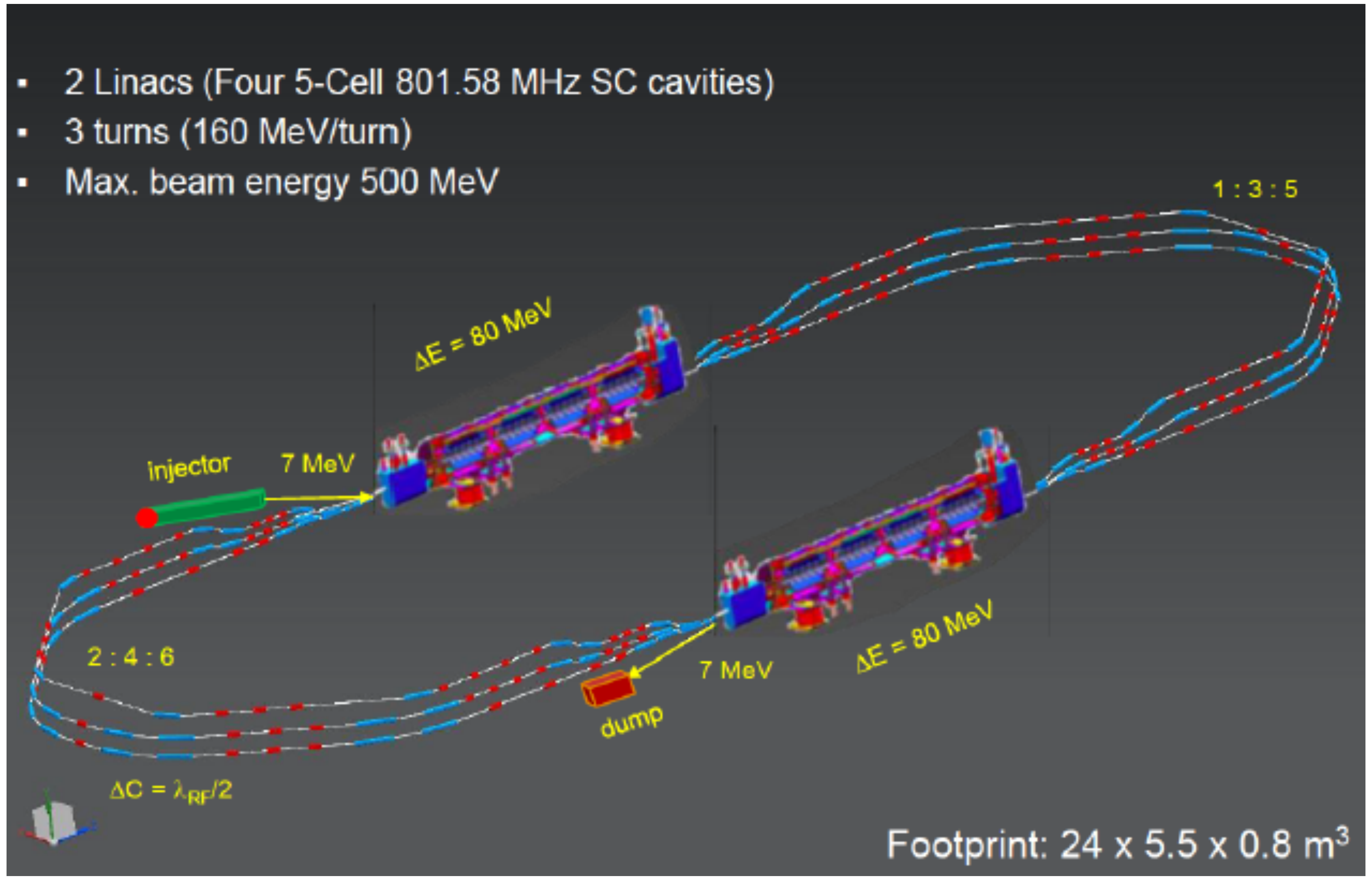
Units: meter (m), Tesla (T), T/m, MHz, MV/m

A. Bogacz, full lattice simulation for ERL at 50 GeV

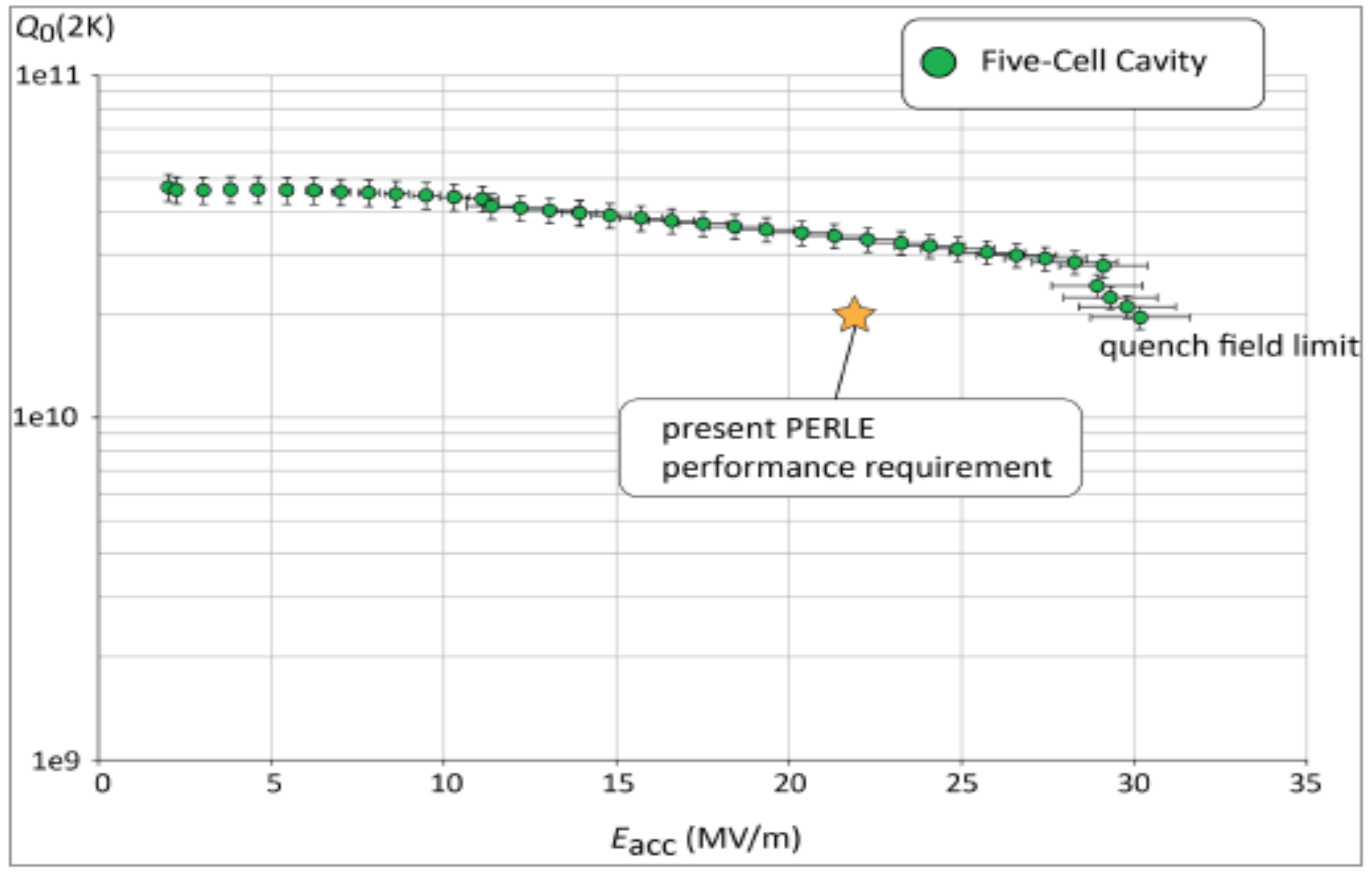
- Cost estimate for 60 / 50 / 30 [phase 1 of 50] GeV E_e: 1.7 / 1.3/ 1.0 BSF [conservative: in doubt took the largest value, resulting estimated for ILC 30% higher than default].
- 802 MHz four 5-cell cavity cryomodule: 112/linac → industrialisation will determine eventual cost; civil engineering gives 265 MSF. O. Brüning at EPS-HEP 2019

PERLE:

- **ERL**: a revolutionary technology ripe for real applications in HEP (ERL for FCC-ee?), low energy and industrial areas, of huge potential just evolving.
- 3-pass, high current demonstrator: PERLE to be built at LAL Orsay, 802 MHz SRF cavities, beam energy 500 MeV for accelerator technology but also for detector and component test, photo-nuclear reactions, proton radius, low energy EW physics,…



- PERLE: BINP, CERN, Daresbury, Liverpool, JLab, Orsay+.
- It could be used as LHeC injector.
- 802 MHz 5-cell Nb cavity built (JLab+CERN): prototype for both LHeC and FCC-ee.



- Ongoing: installation of the e-gun, construction of the second cavity, design of criomodule and HOM coupling, radiation protection, hirings.

PERLE:

Project staging strategy:

The PERLE configuration entails the possibility to construct PERLE in stages. We propose in the following two main phases to attend the final configuration.

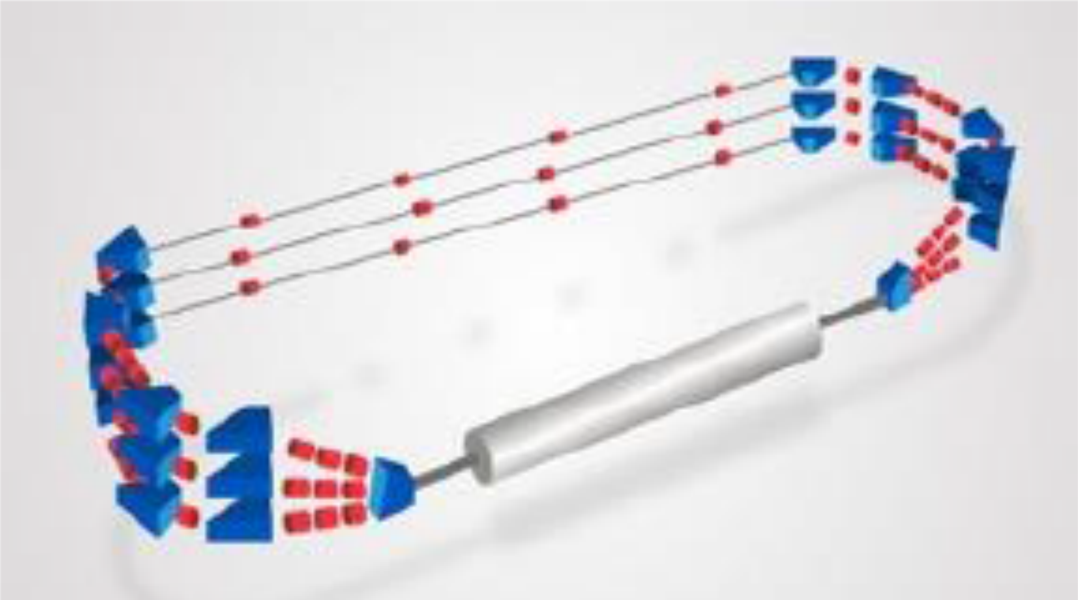
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ To allow a rather rapid realisation of a 250 MeV machine.

→ To test with beam the various SRF components.

→ To prove the multi-turn ERL operation.

→ to gain essential operation experience.



PERLE Phase 1 layout

Phase 2 : Realisation of PERLE at its design parameters as a 10MW machine:

→ Upgrade of the e- gun

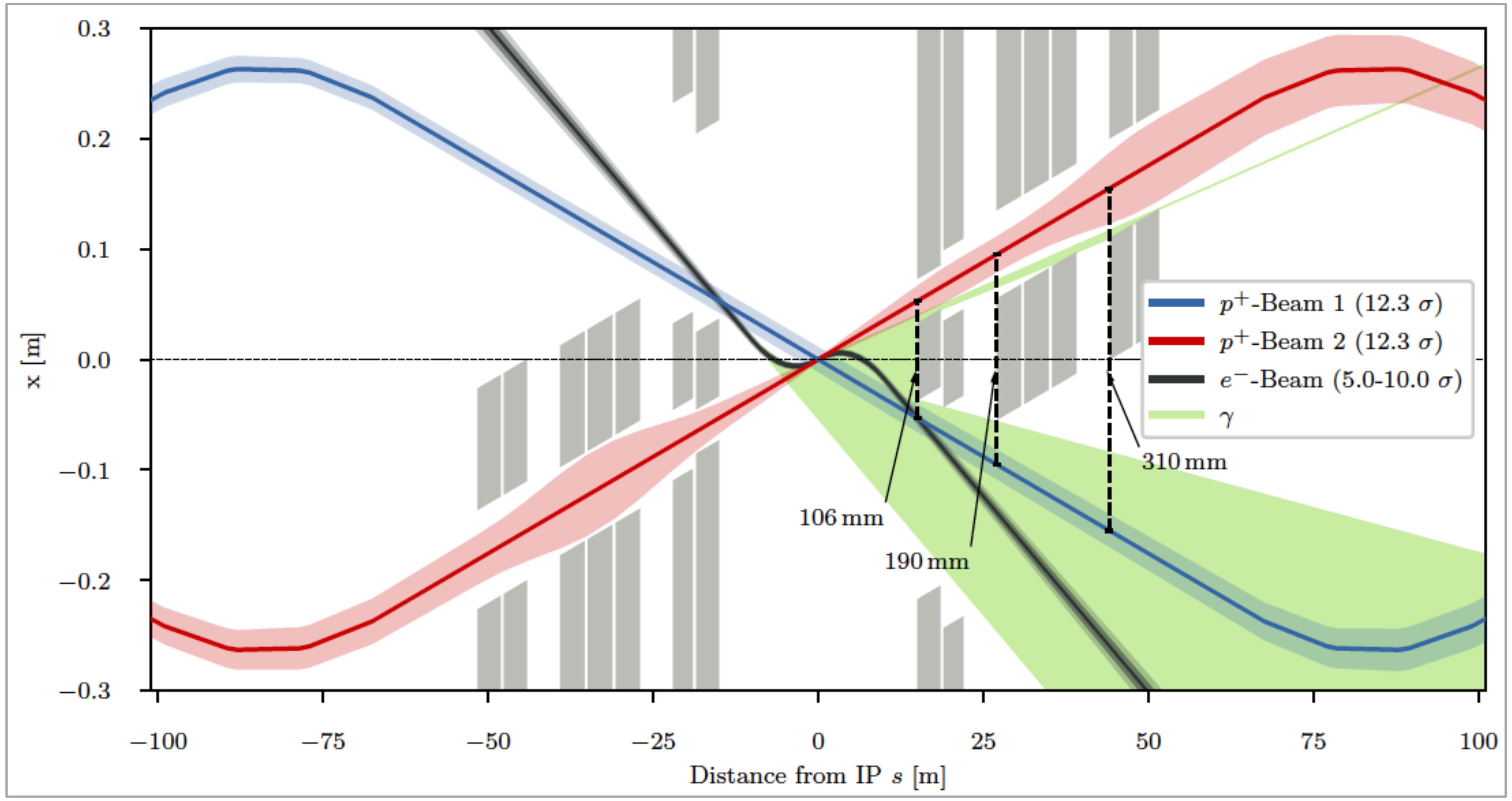
→ Installation of the 2nd Spreader and recombinar

→ Installation of the second cryomodule in the second straight.

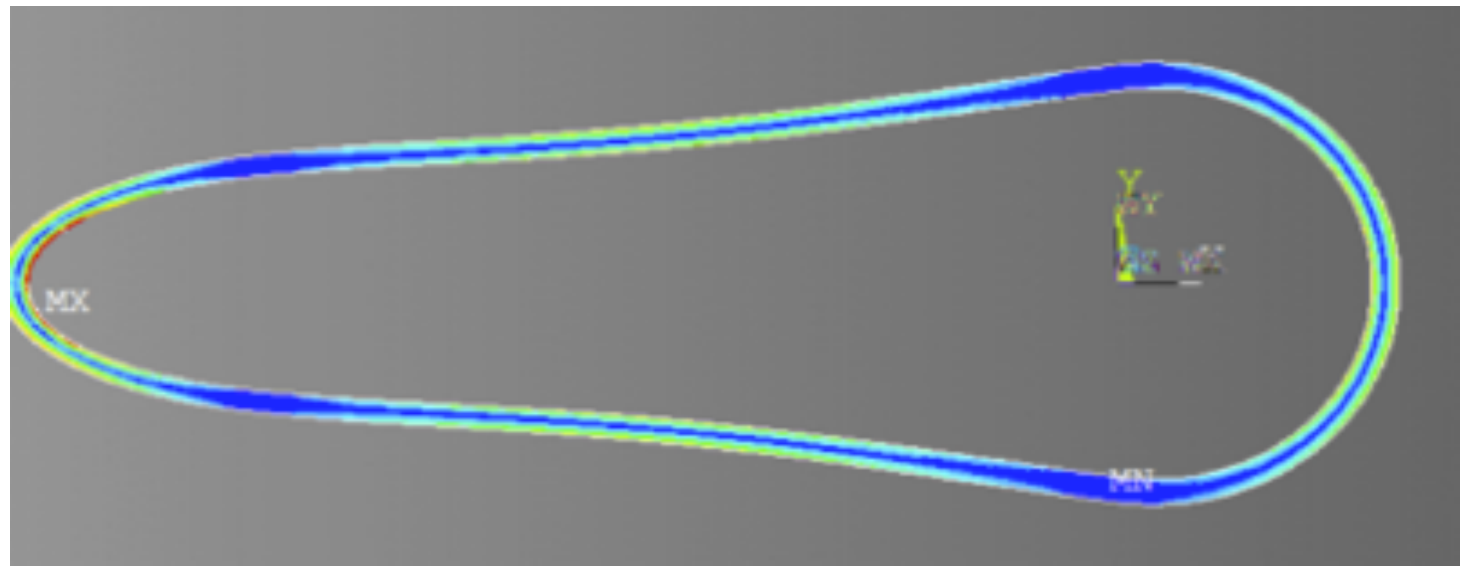
PERLE Phase 2 layout

Walid Kaabi (Orsay) FCC Week 2019 - Brussels, 27 June 2019 9

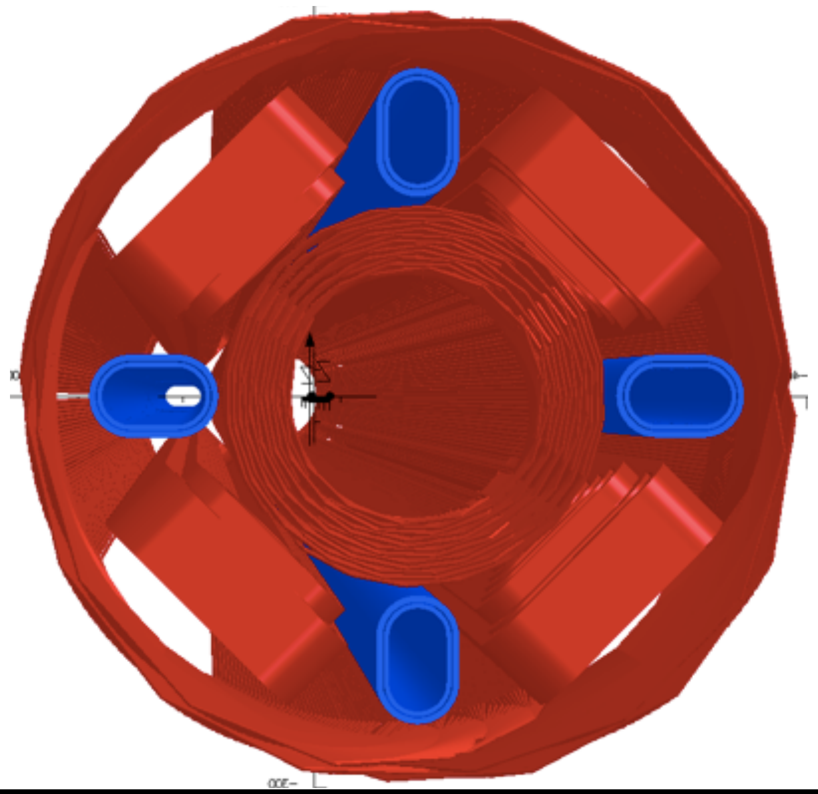
Interaction region:



- Need to bend the electron (dipoles close to the interaction point) and to accommodate 3 beams: design of IR crucial.



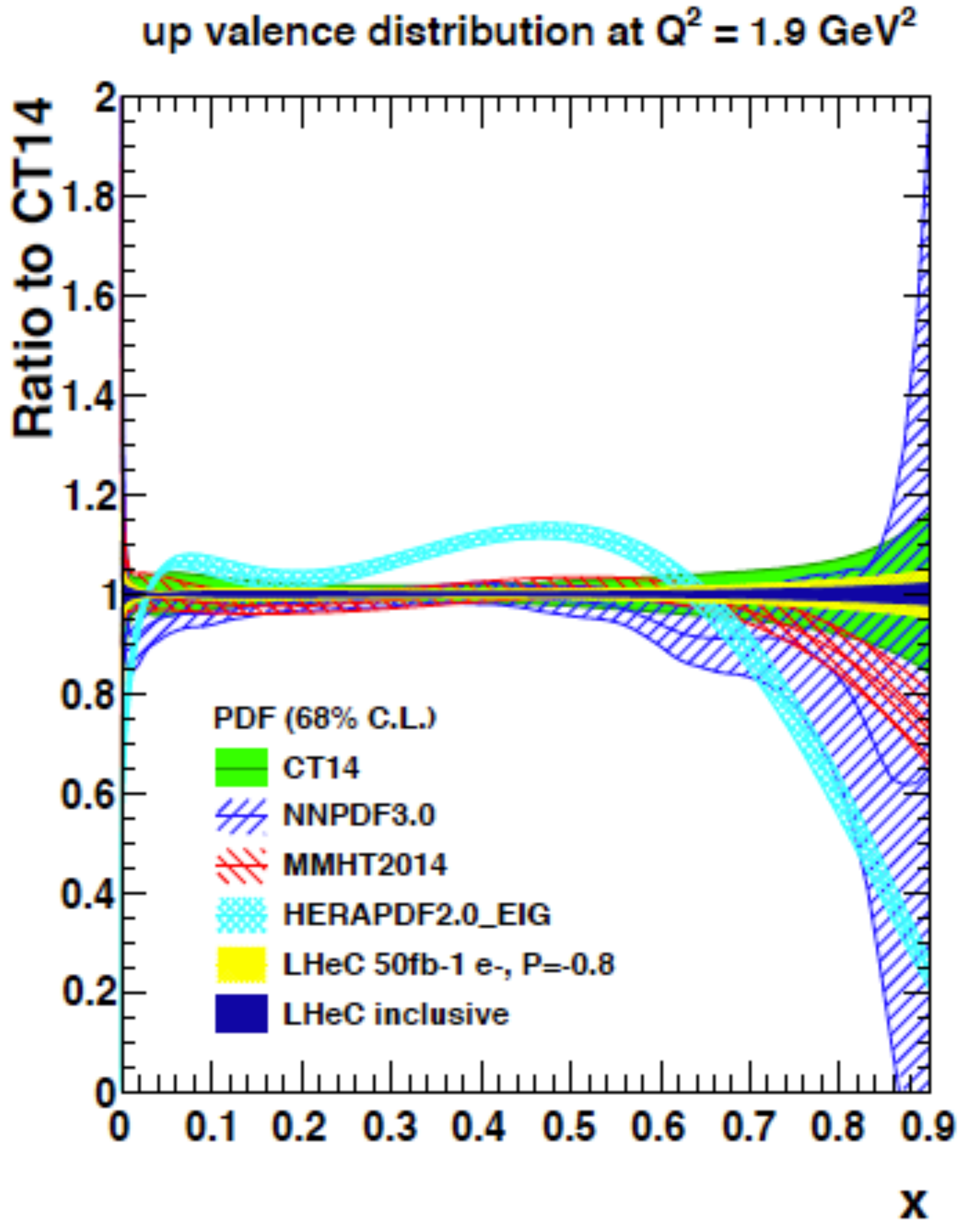
- Design of the quadrupoles and synchrotron radiation shielding ongoing.

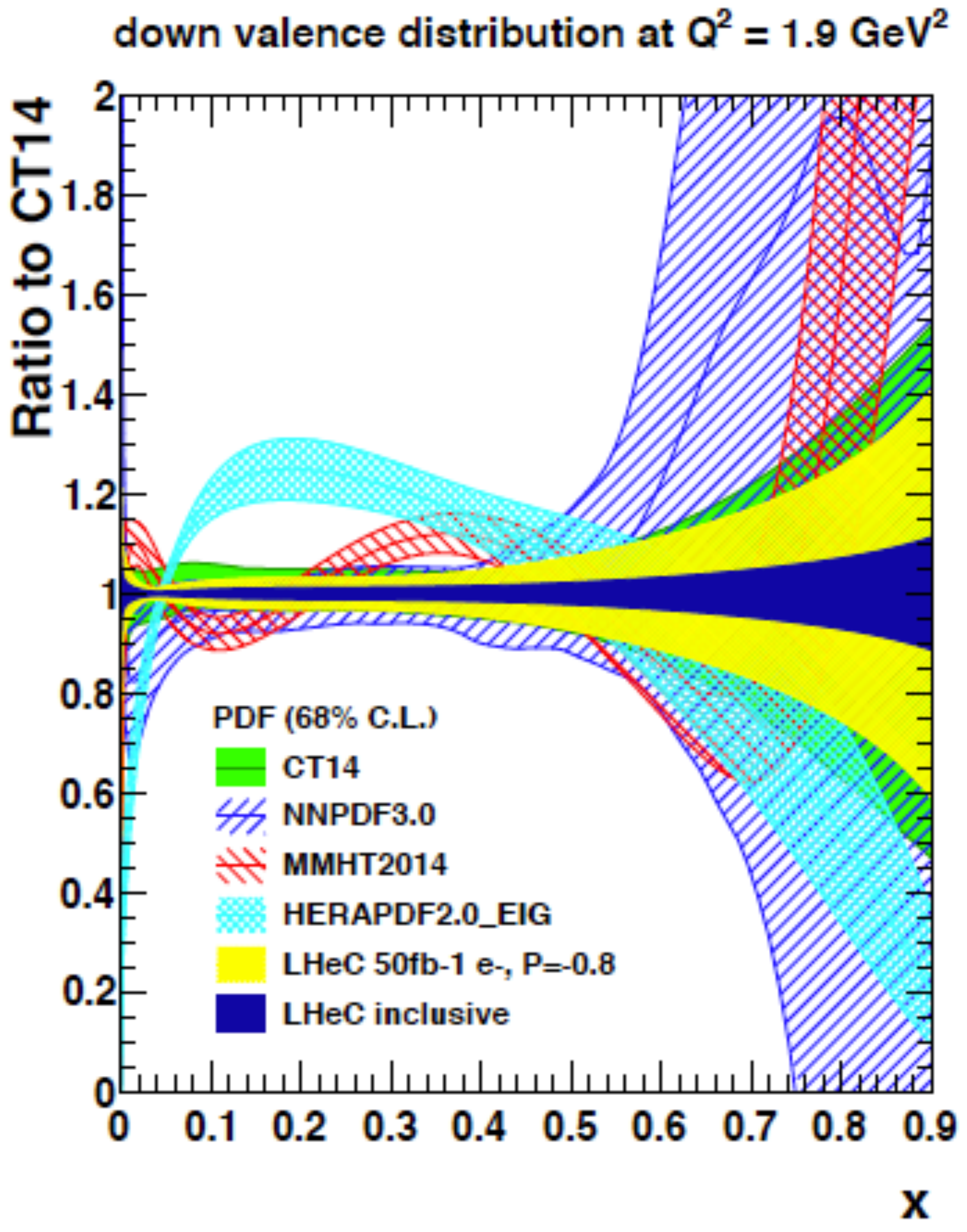


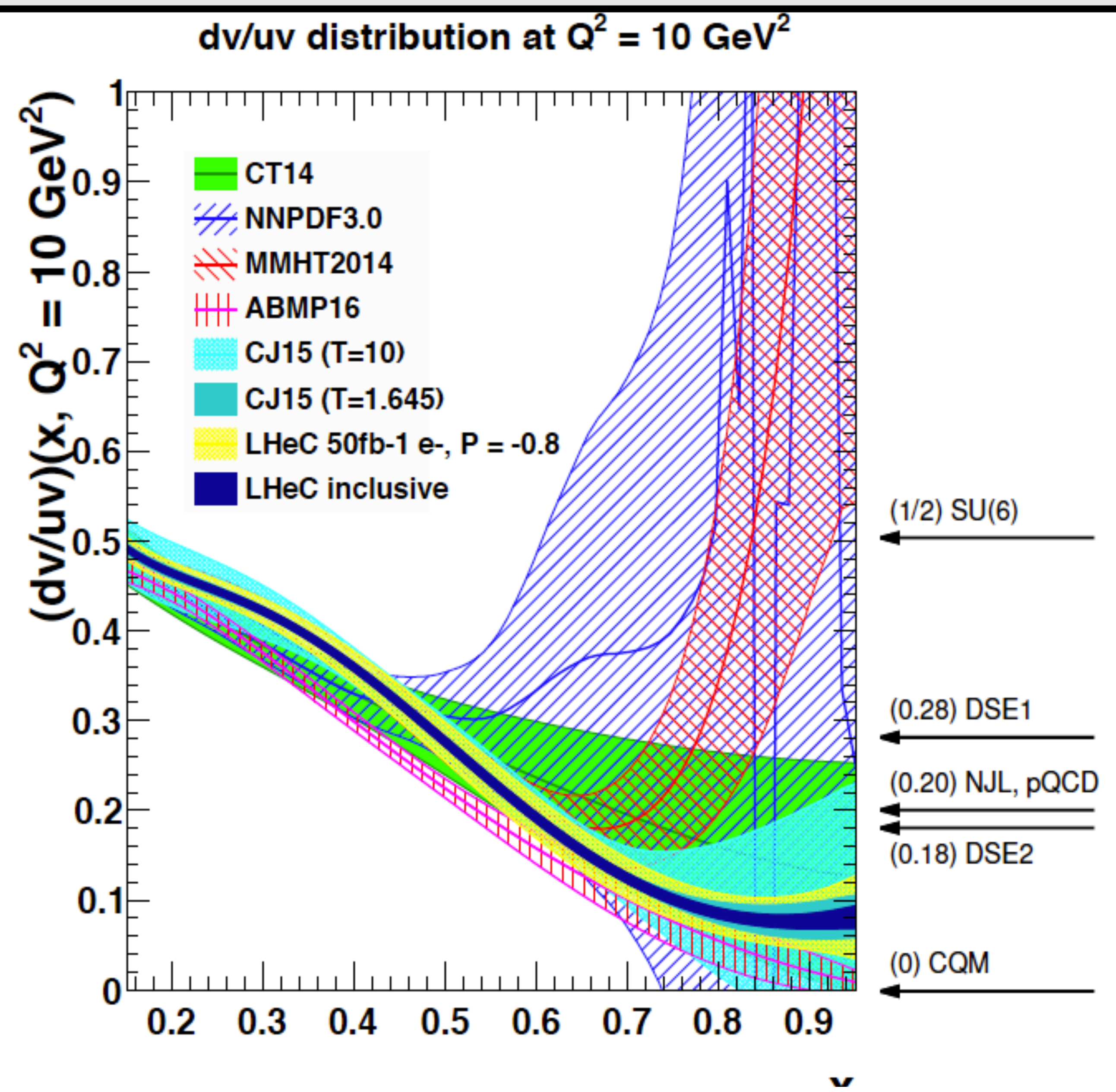
Synchrotron radiation	HERA	LHeC
E_{crit} [KeV]	150	~280
Power	28	~40

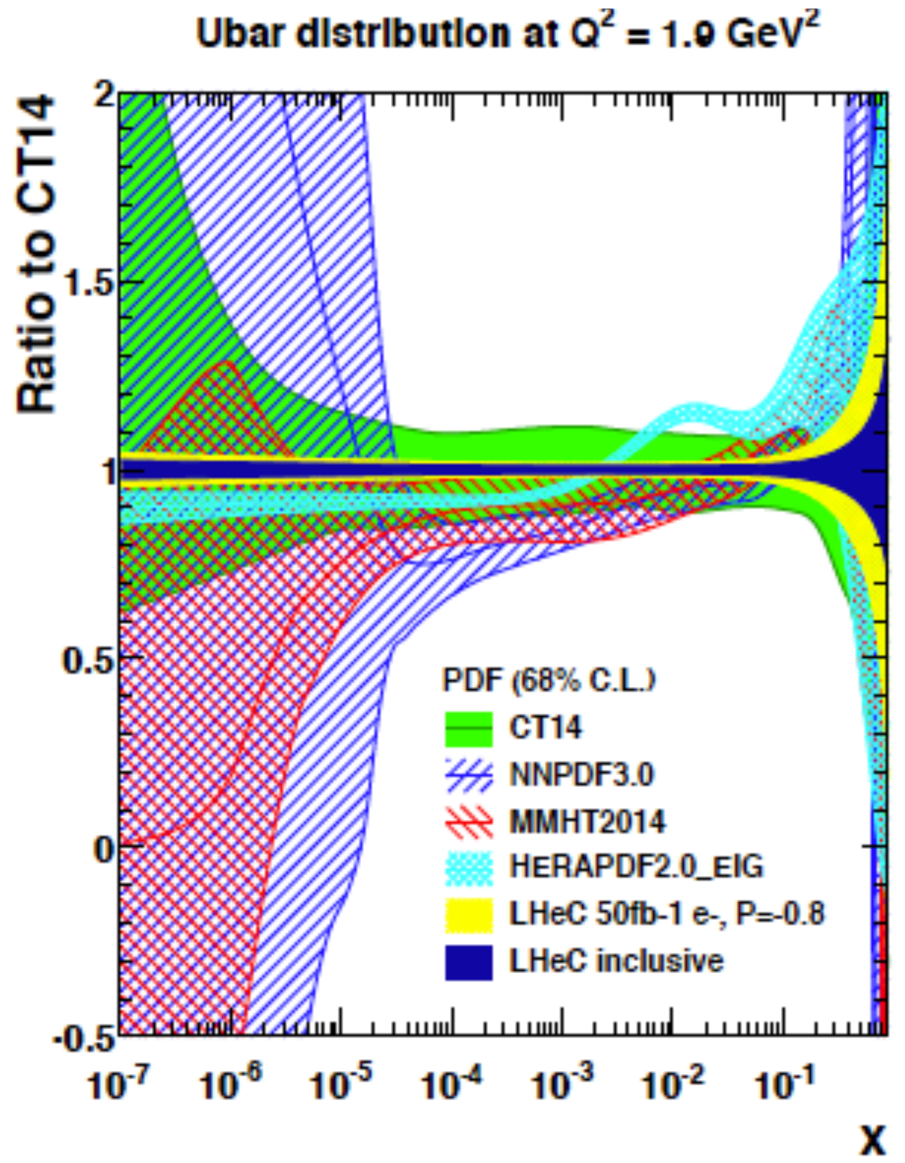
QCD: parton densities

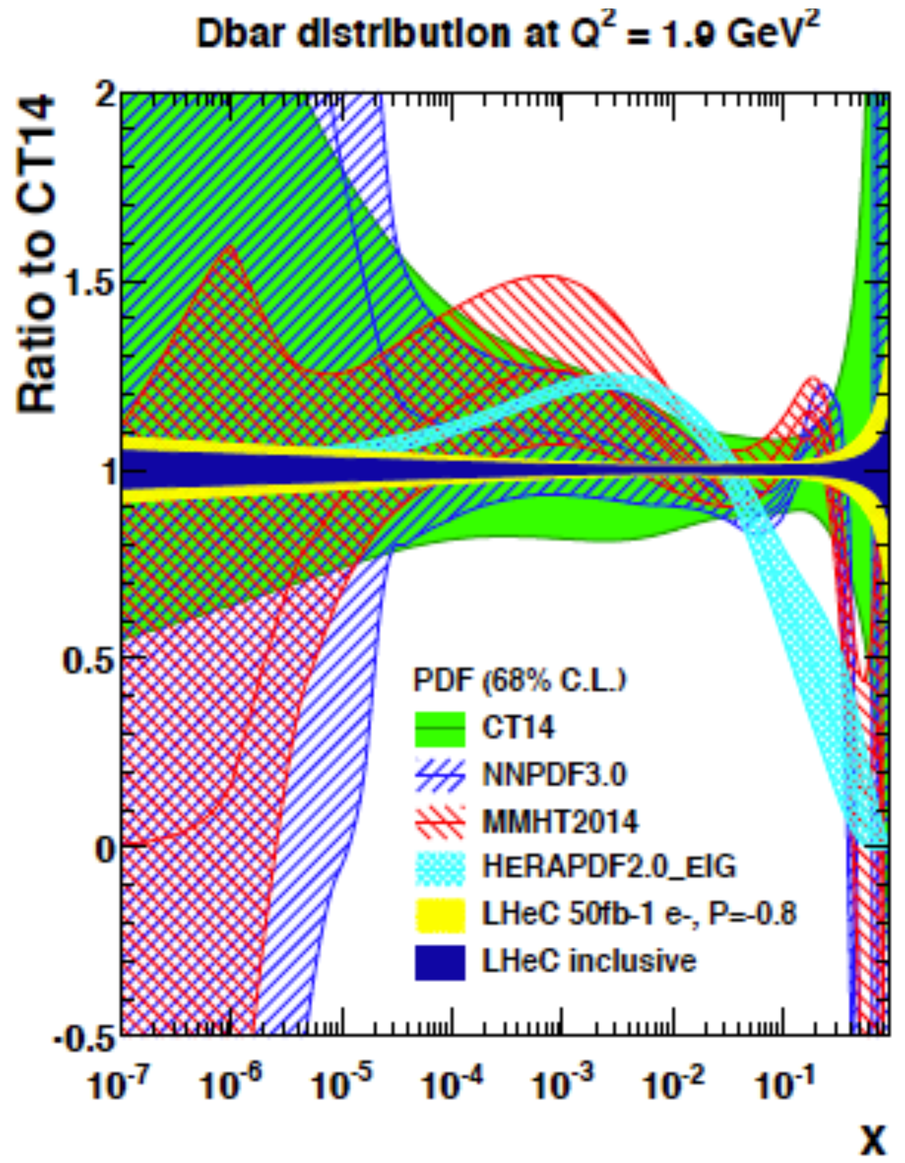
- For the first time: complete resolution of flavour and gluon parton substructure: system/ experiment, in unprecedented kinematic range (no higher twists, no nuclear corrections,…):

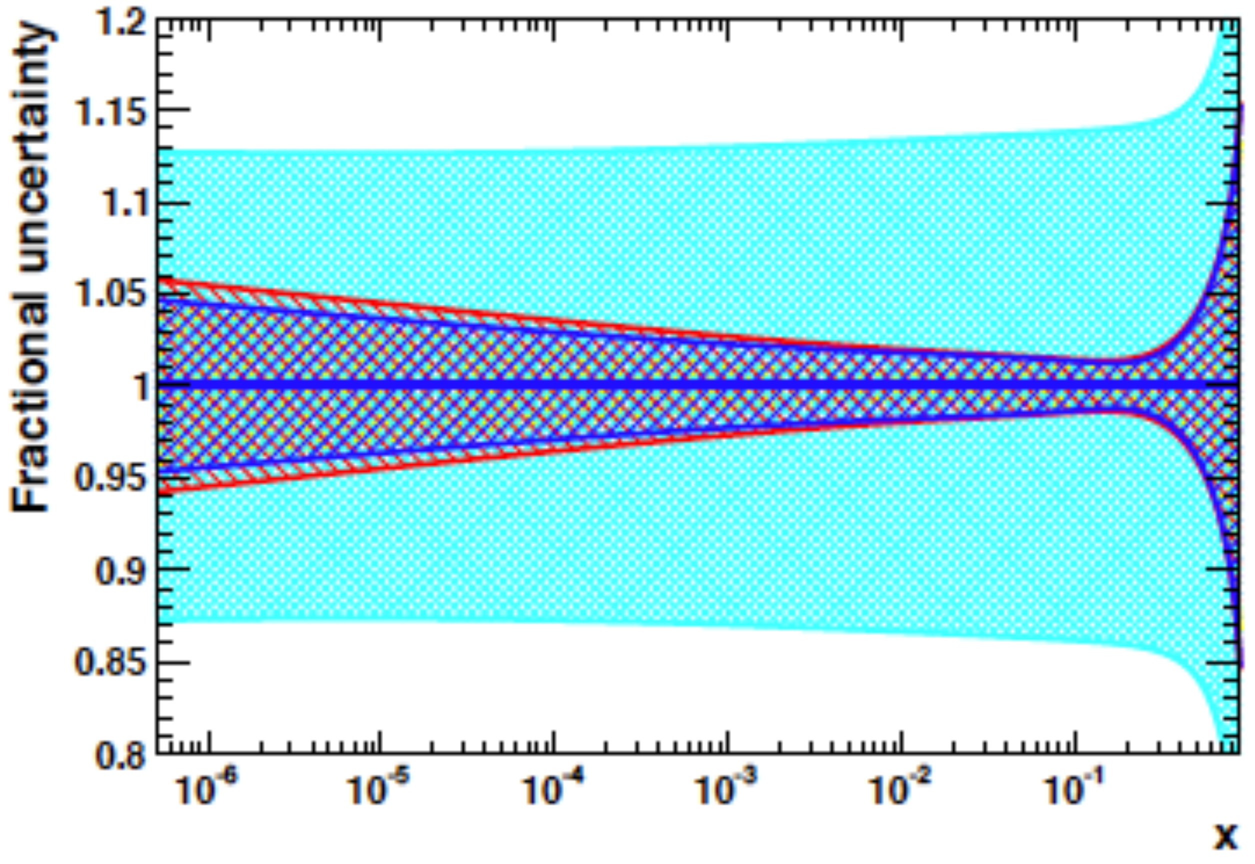










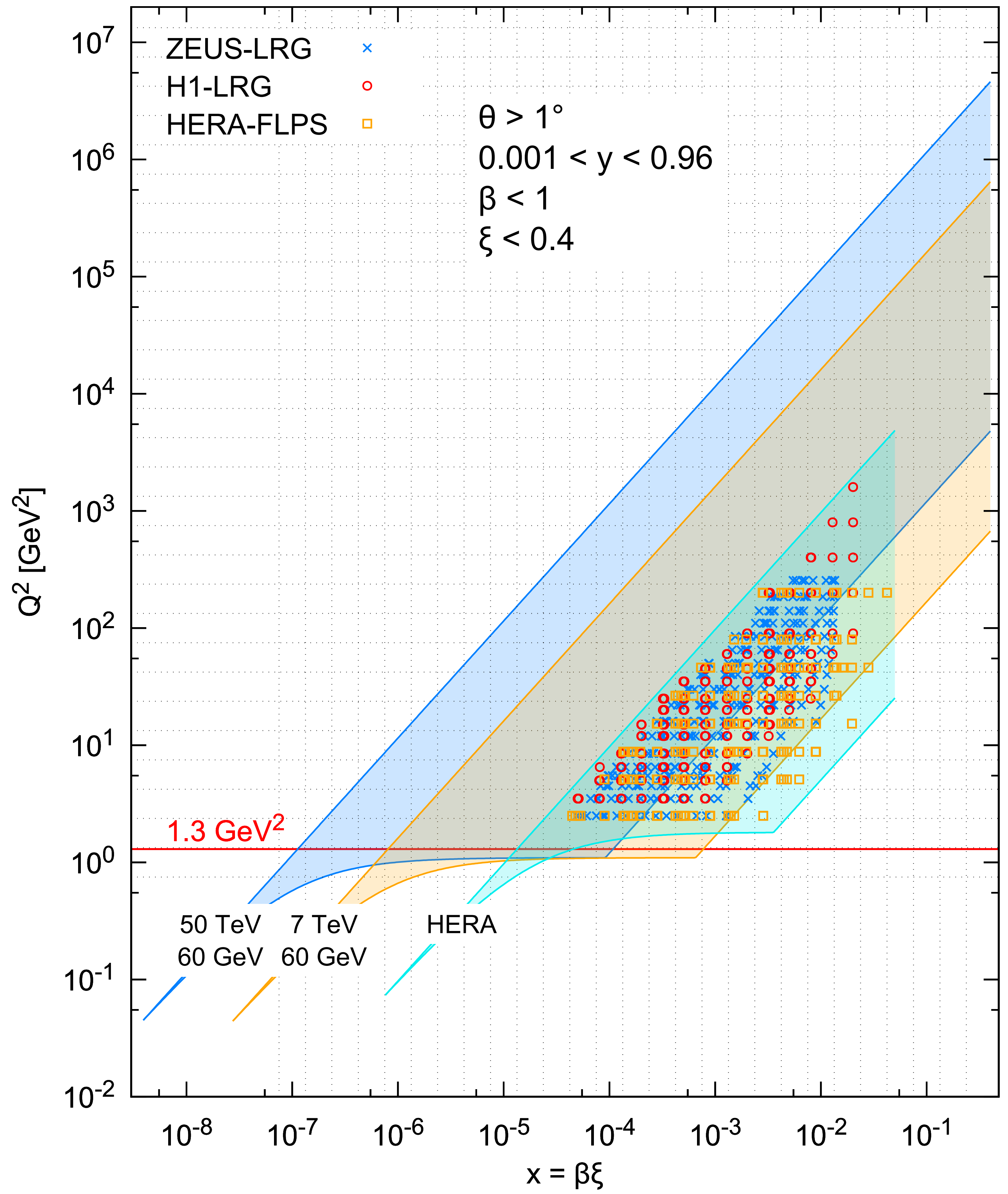


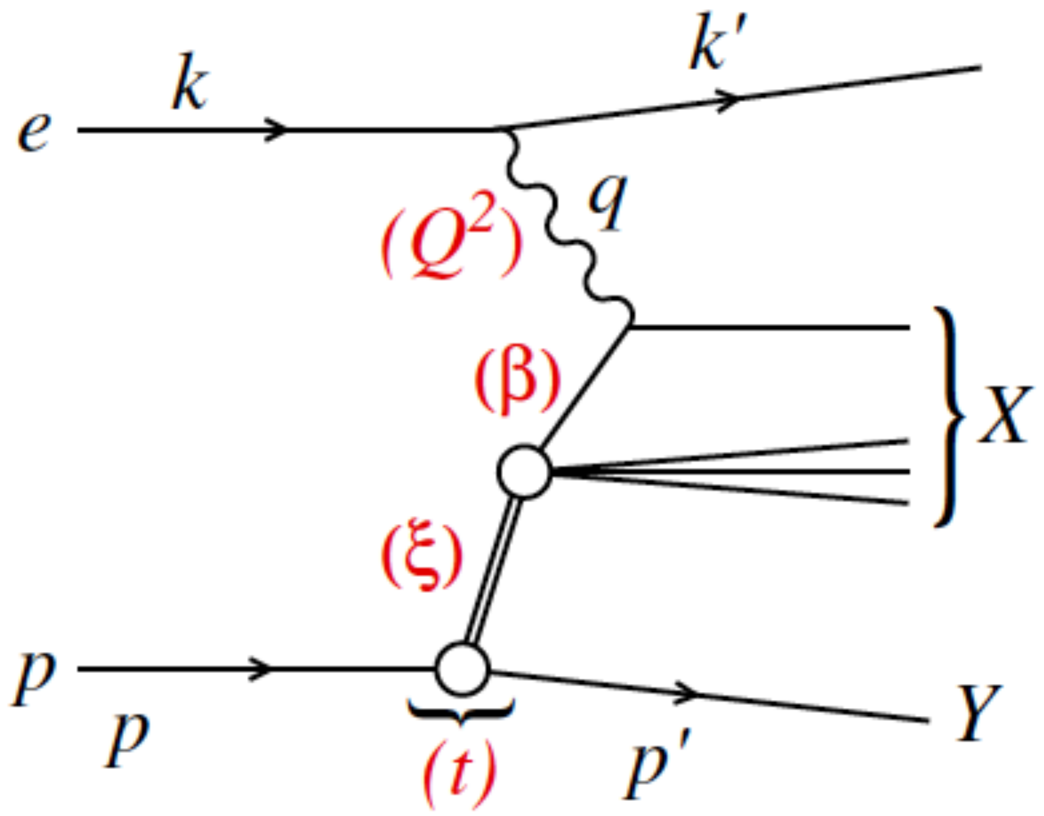
(b) $x\bar{s}$ quark distribution.

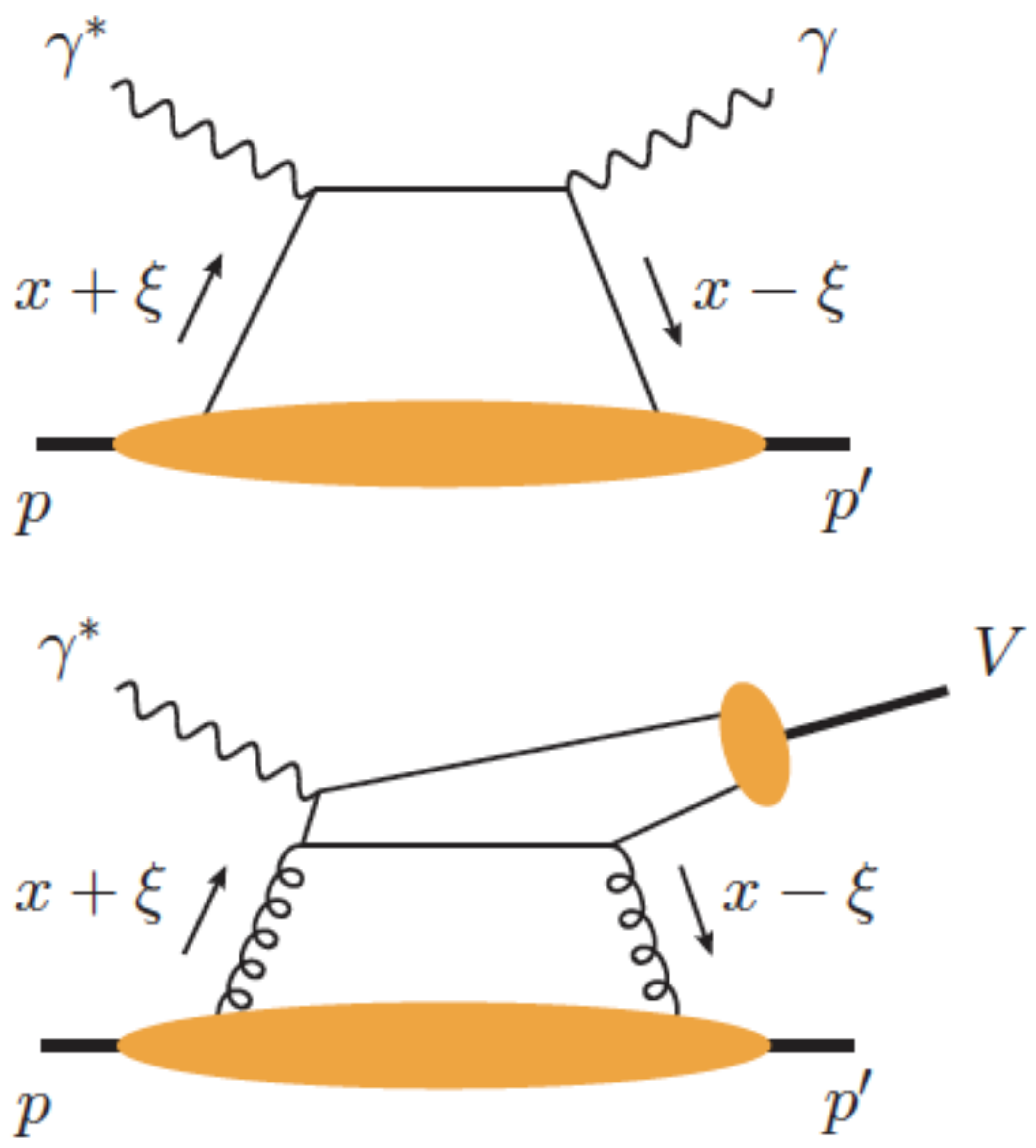
Diffraction and transverse structure:

- Diffraction: probability of ep inelastic interaction keeping the proton intact (10-15 % at HERA).

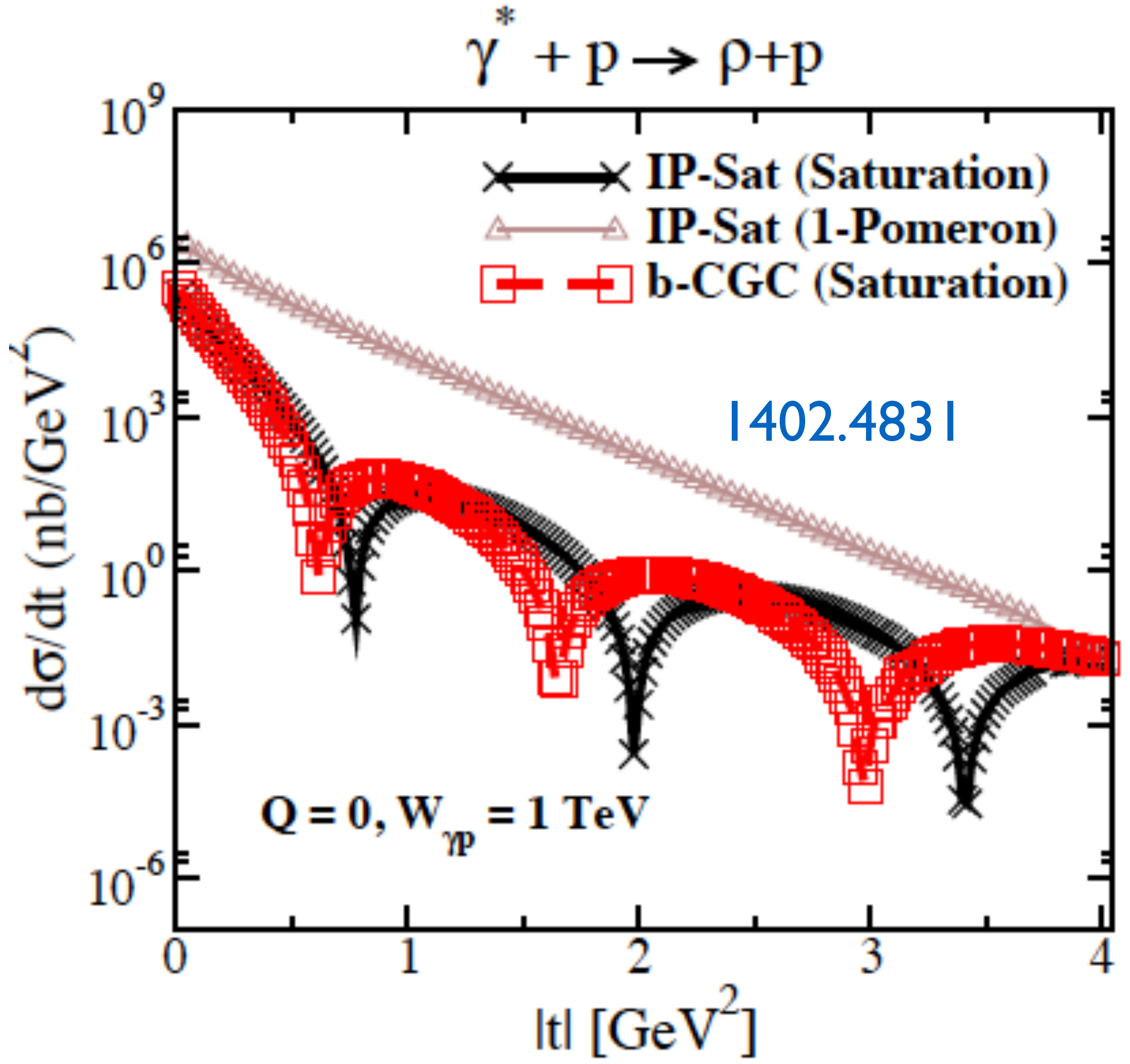
- Inclusive diffraction: precise determination of diffractive PDFs.



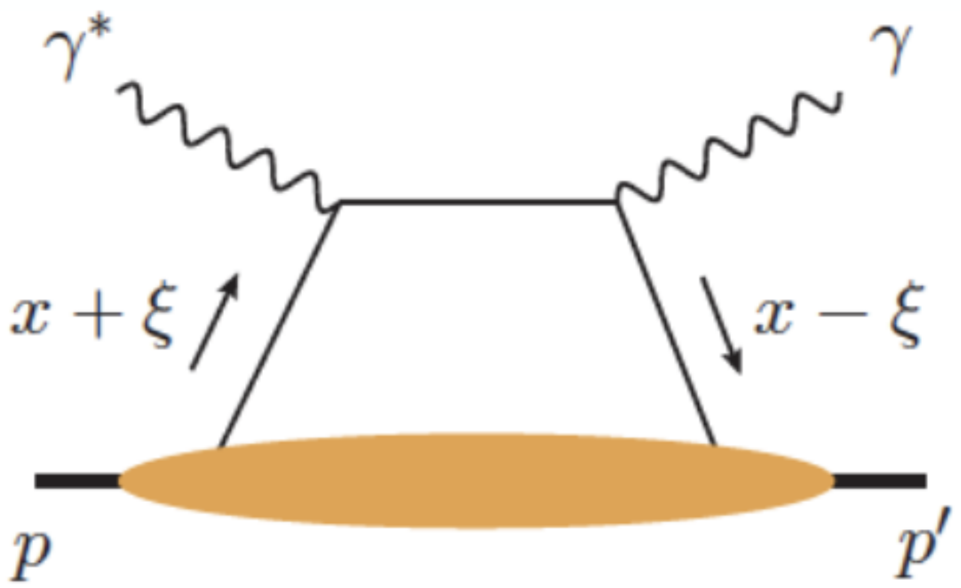


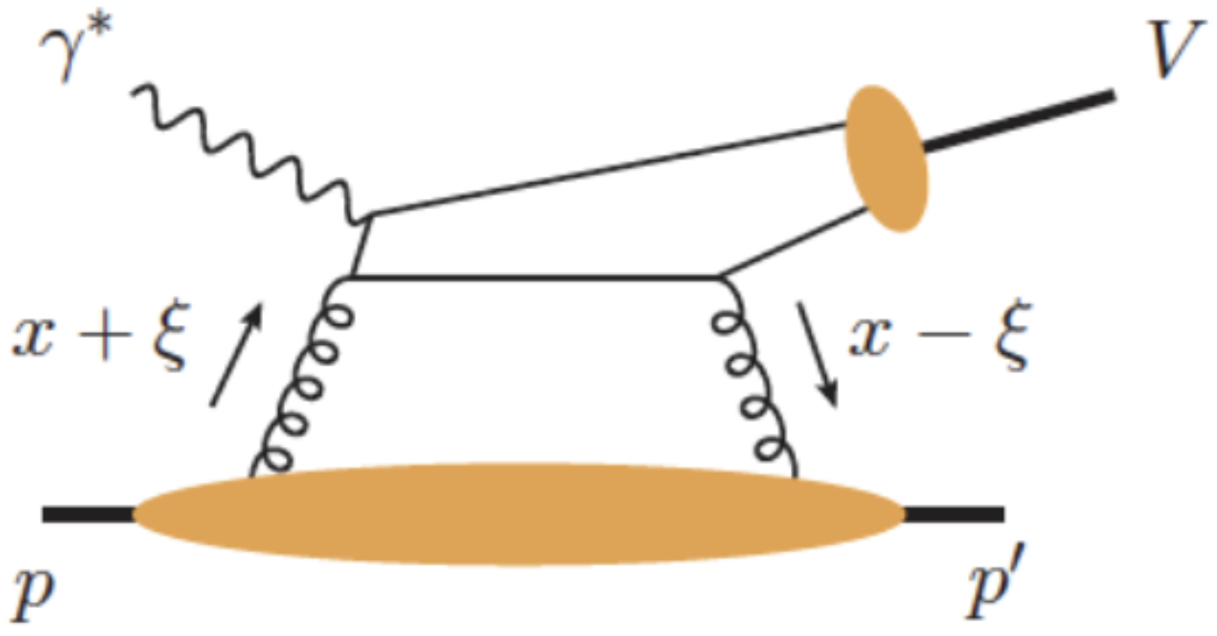


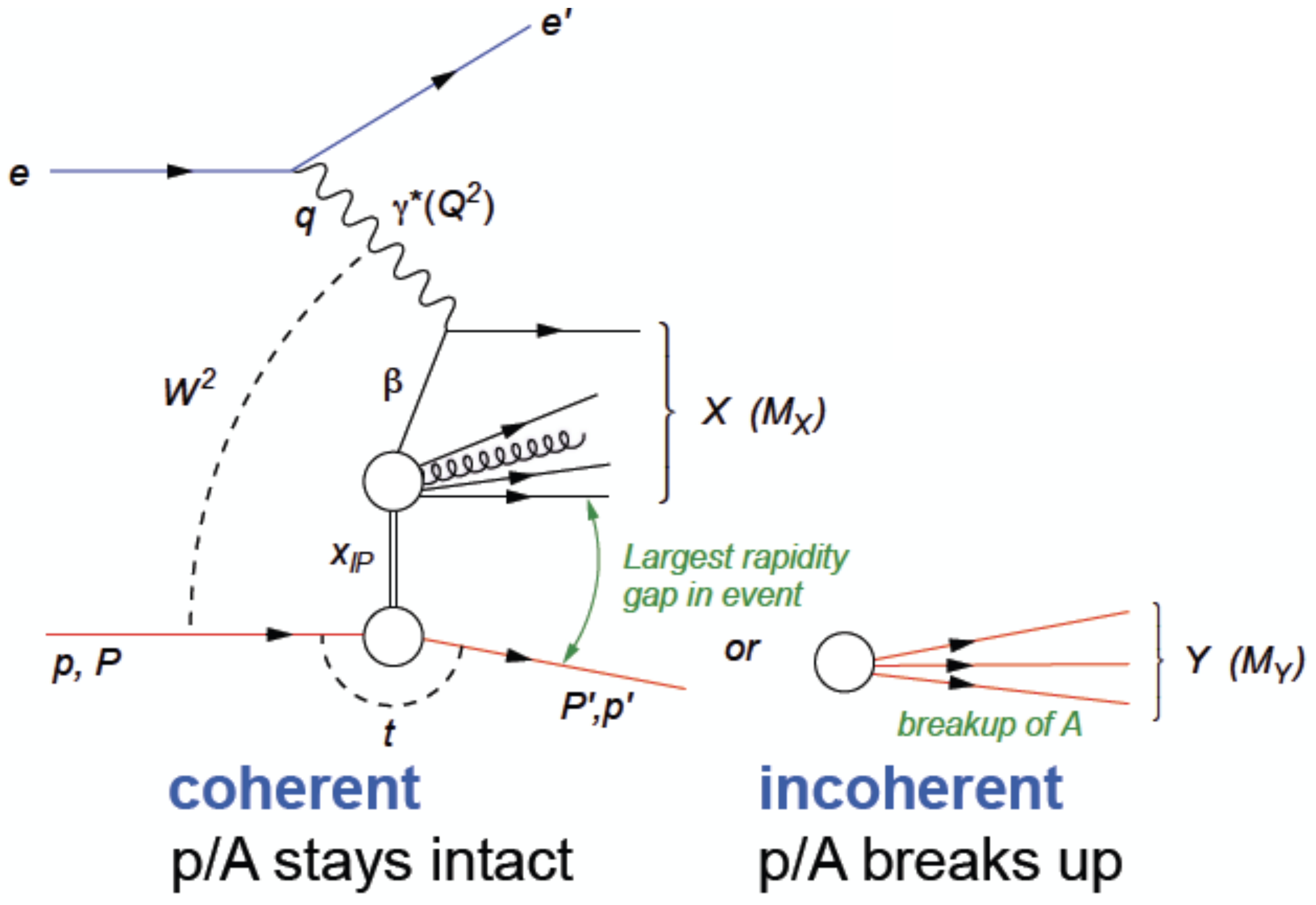
- Exclusive diffraction: transverse partonic structure, hot spots (fluctuations of density in coherent ep→eXp versus incoherent ep→eXp*).



Quark and gluon GPDs:



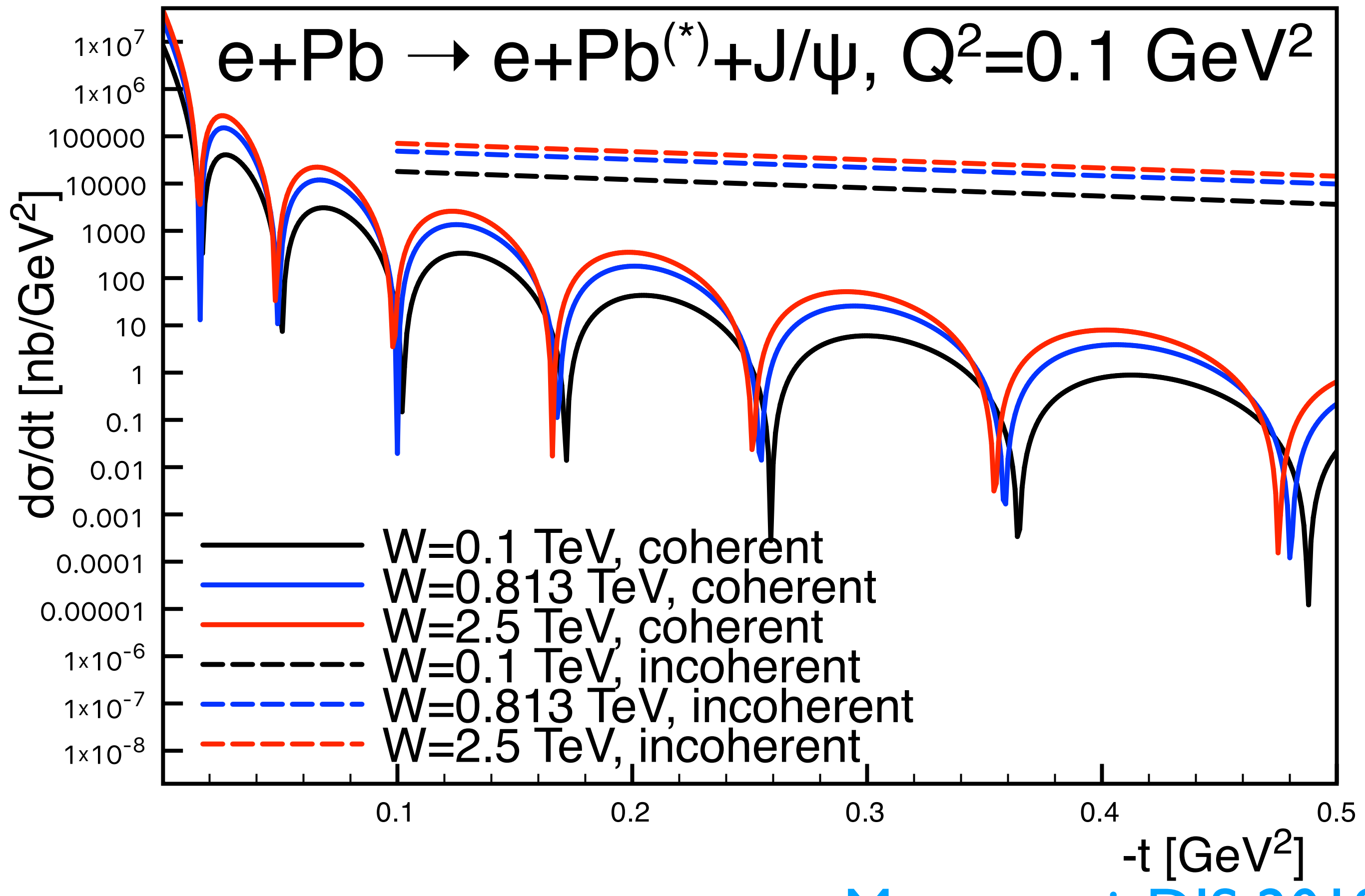


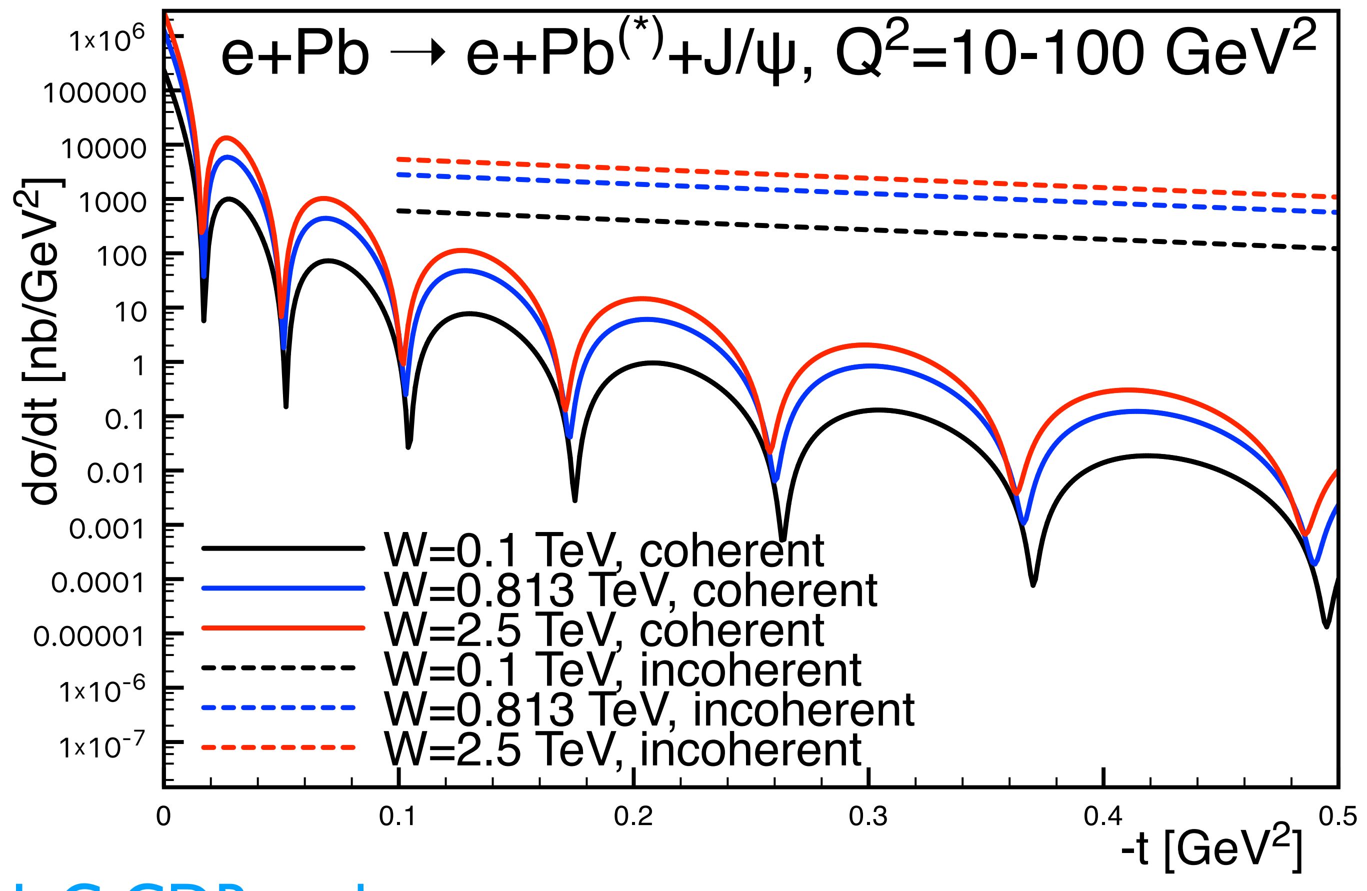


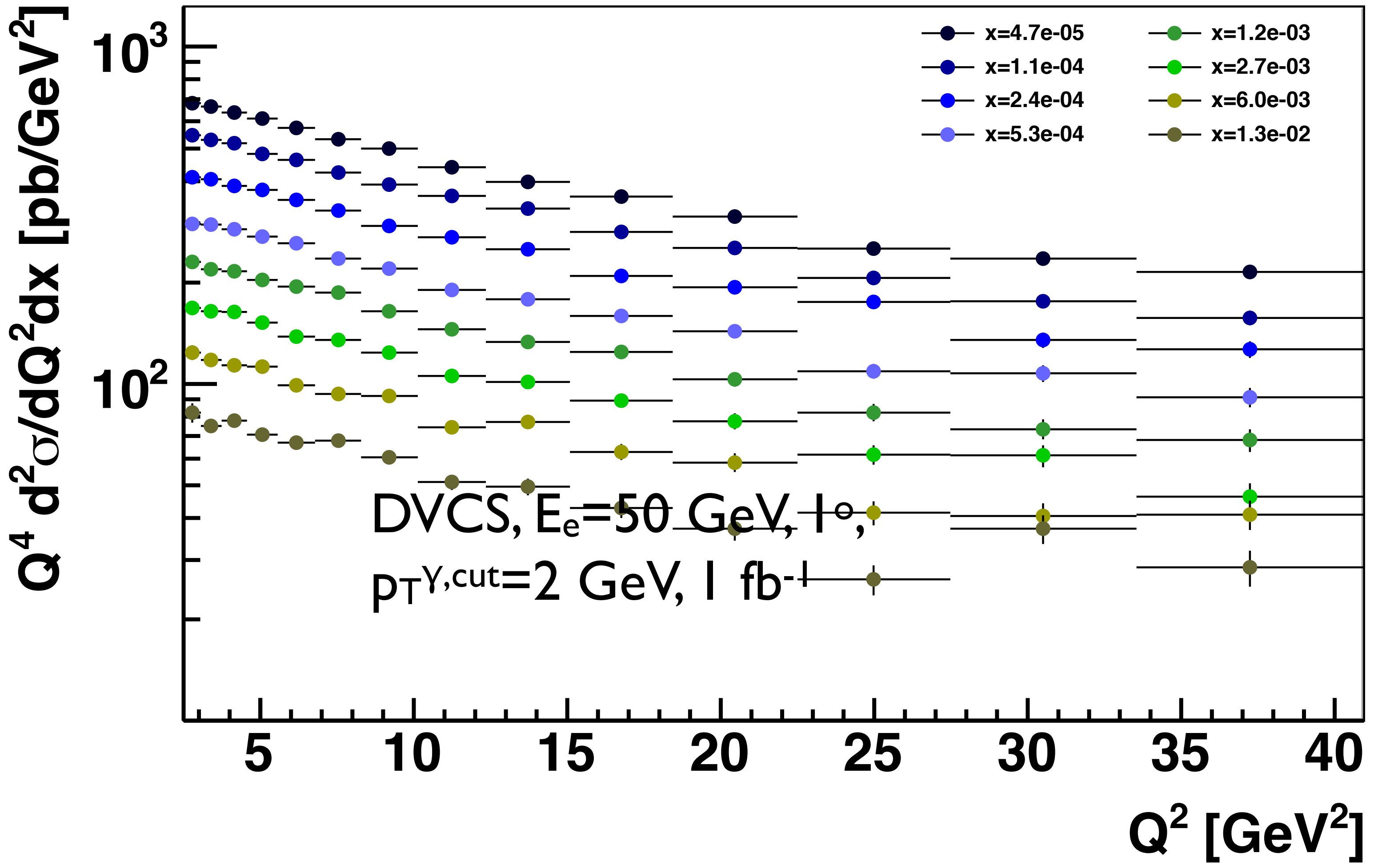
$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T\bar{\psi}_j\left(0,\frac{1}{2}w^-,\mathbf{0}_\mathrm{T}\right)\frac{\gamma^+}{2}\psi_j\left(0,-\frac{1}{2}w^-,\mathbf{0}_\mathrm{T}\right)\middle| P\right\rangle_\mathrm{c}$$

- Coherent exclusive production of γ and VM yields information about q and g GPDs.

LHeC 1206.2913

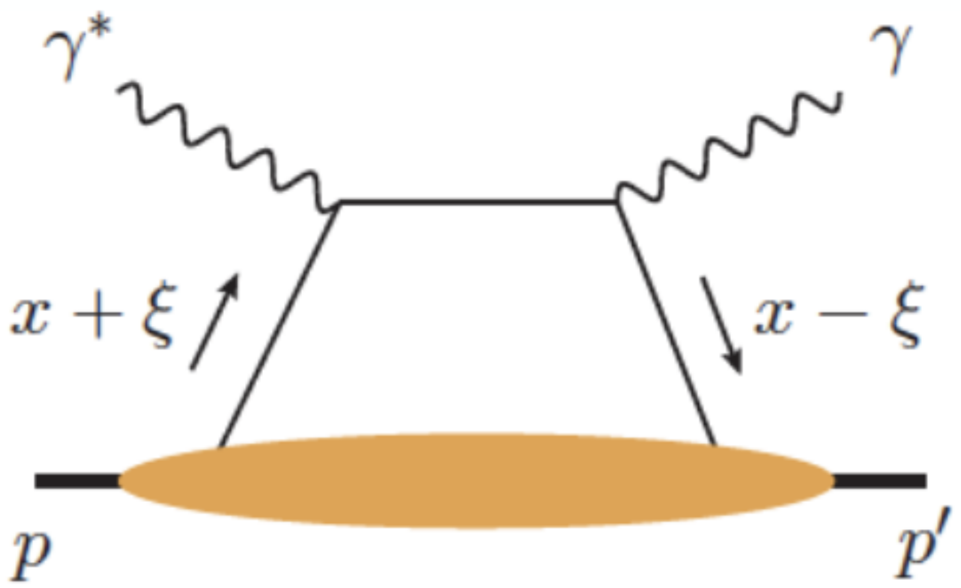


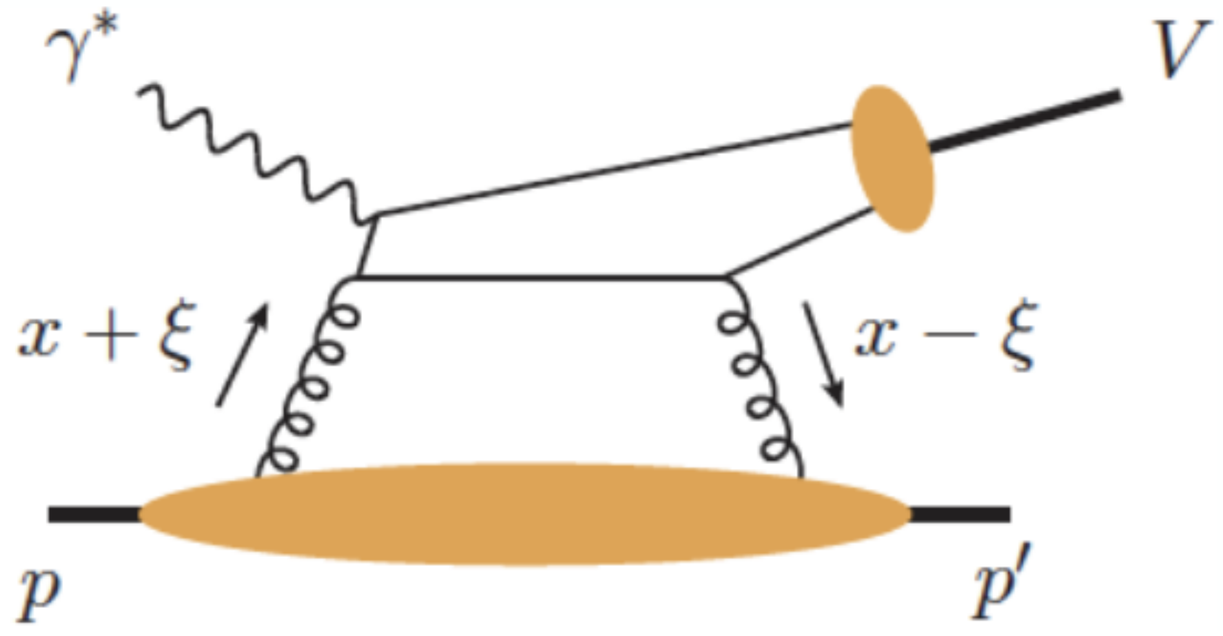


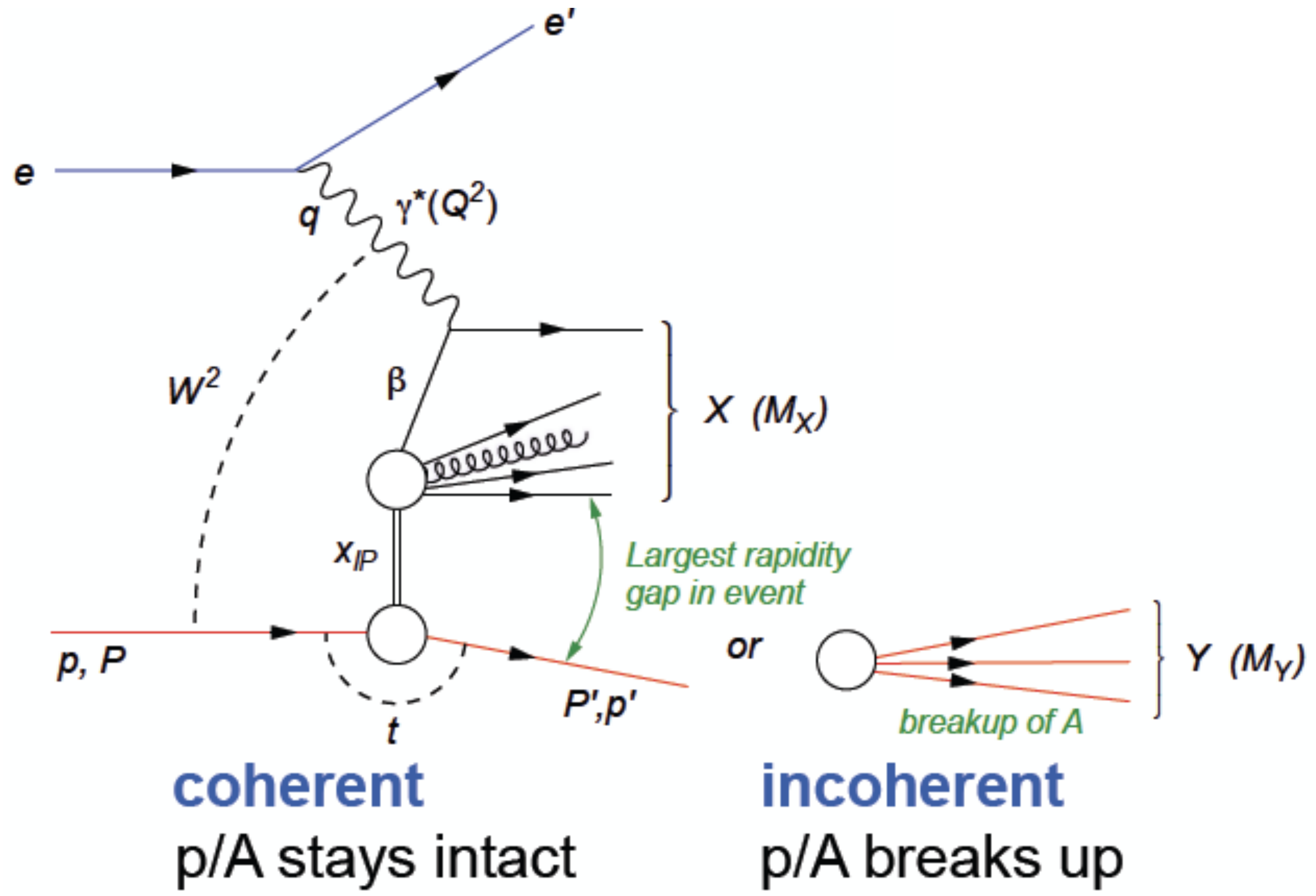


Mantysaari, DIS 2018, LHeC CDR update to appear

Quark and gluon GPDs:

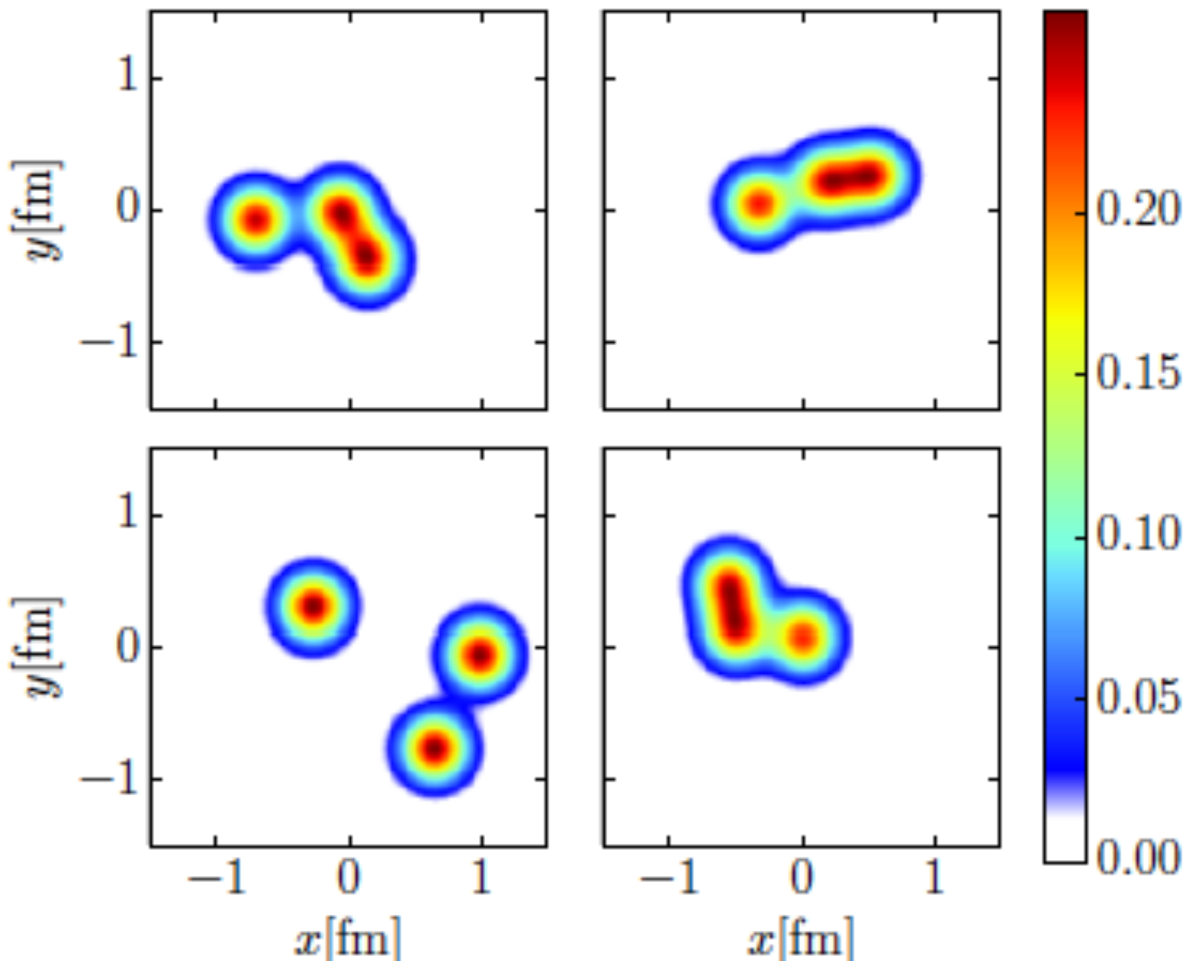


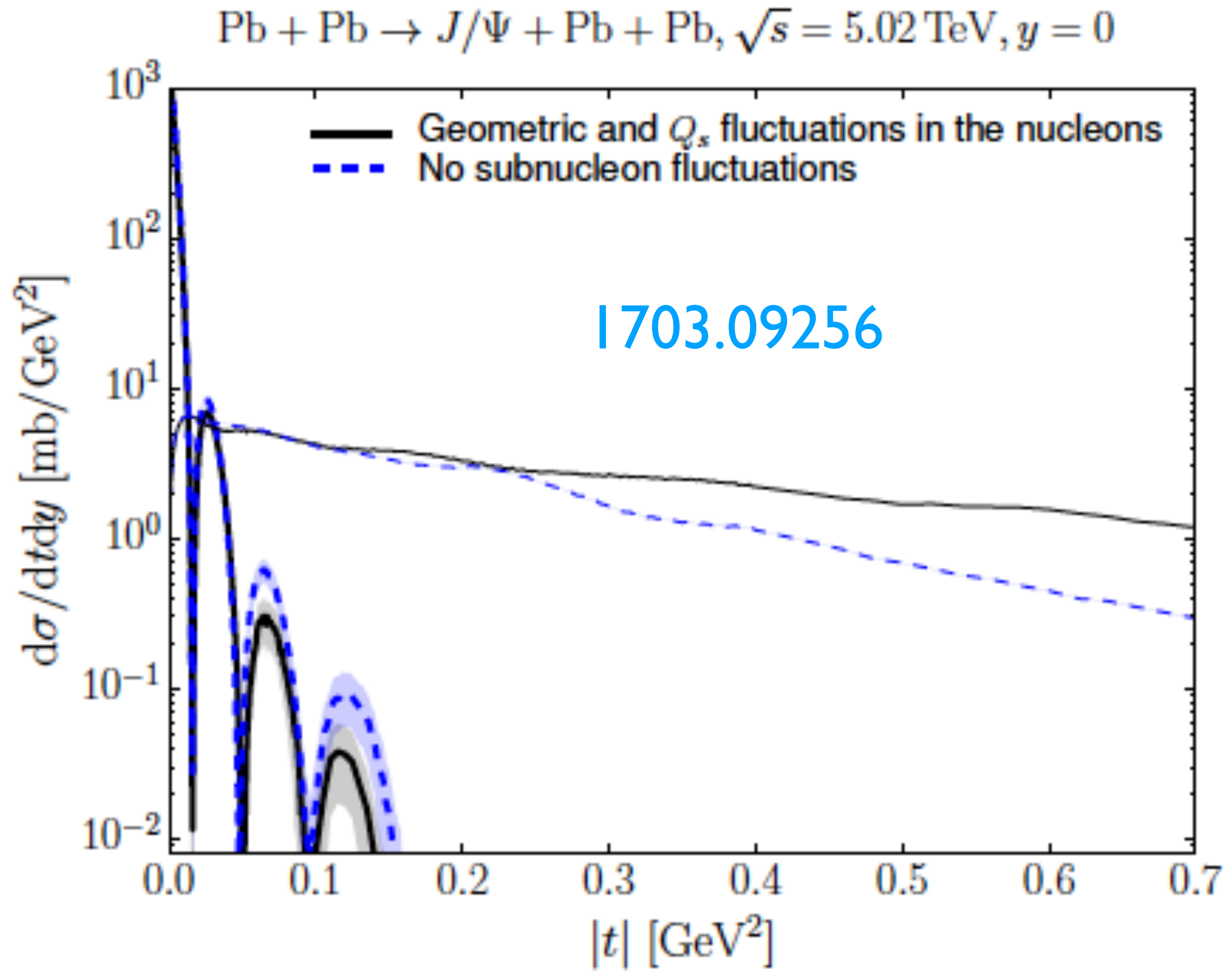




$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T \overline{\psi}_j \left(0, \frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \frac{\gamma^+}{2} \psi_j \left(0, -\frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \middle| P \right\rangle_c$$

- Coherent exclusive production of γ and VM yields information about q and g GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots.



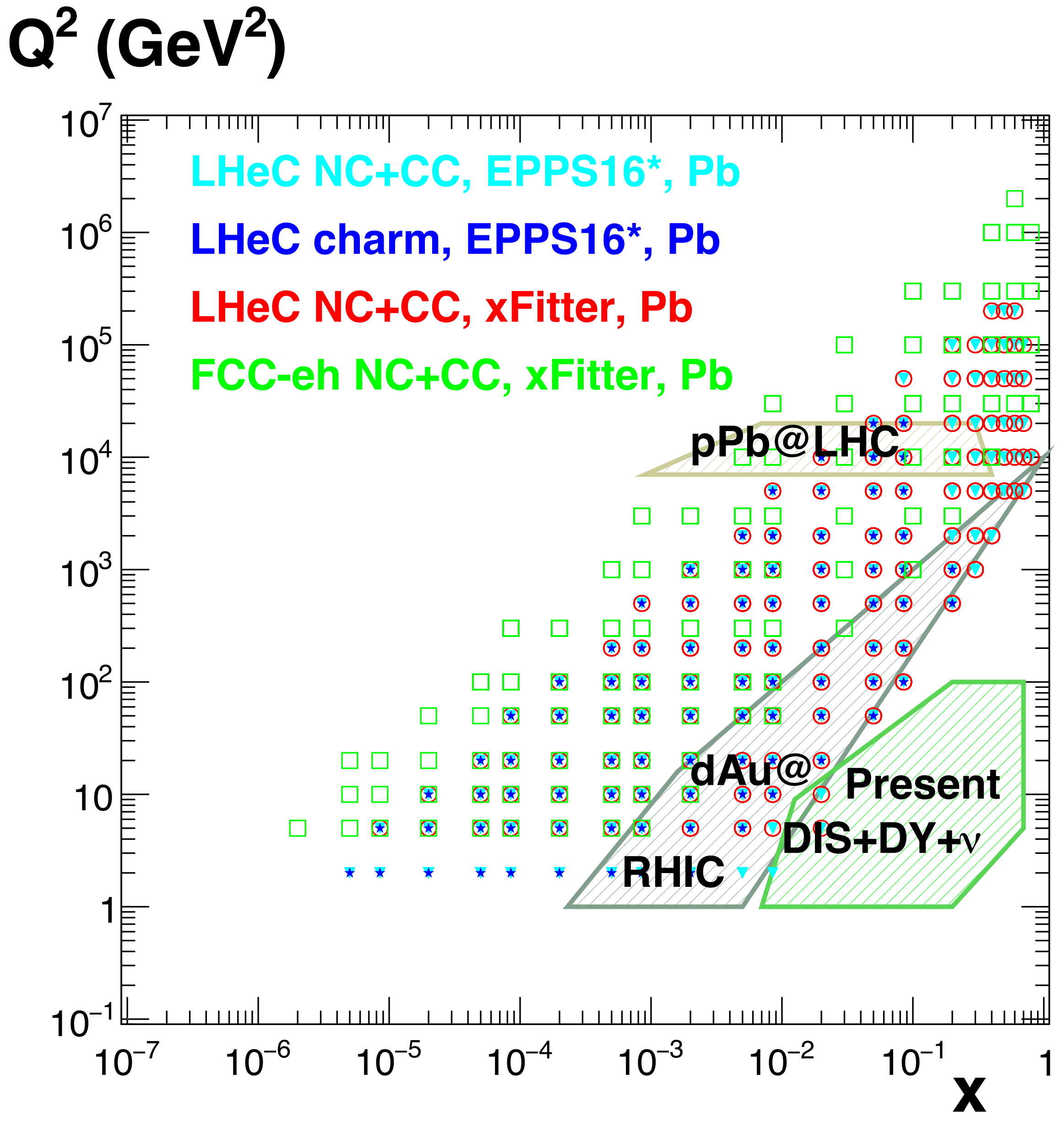


nPDFs: fits

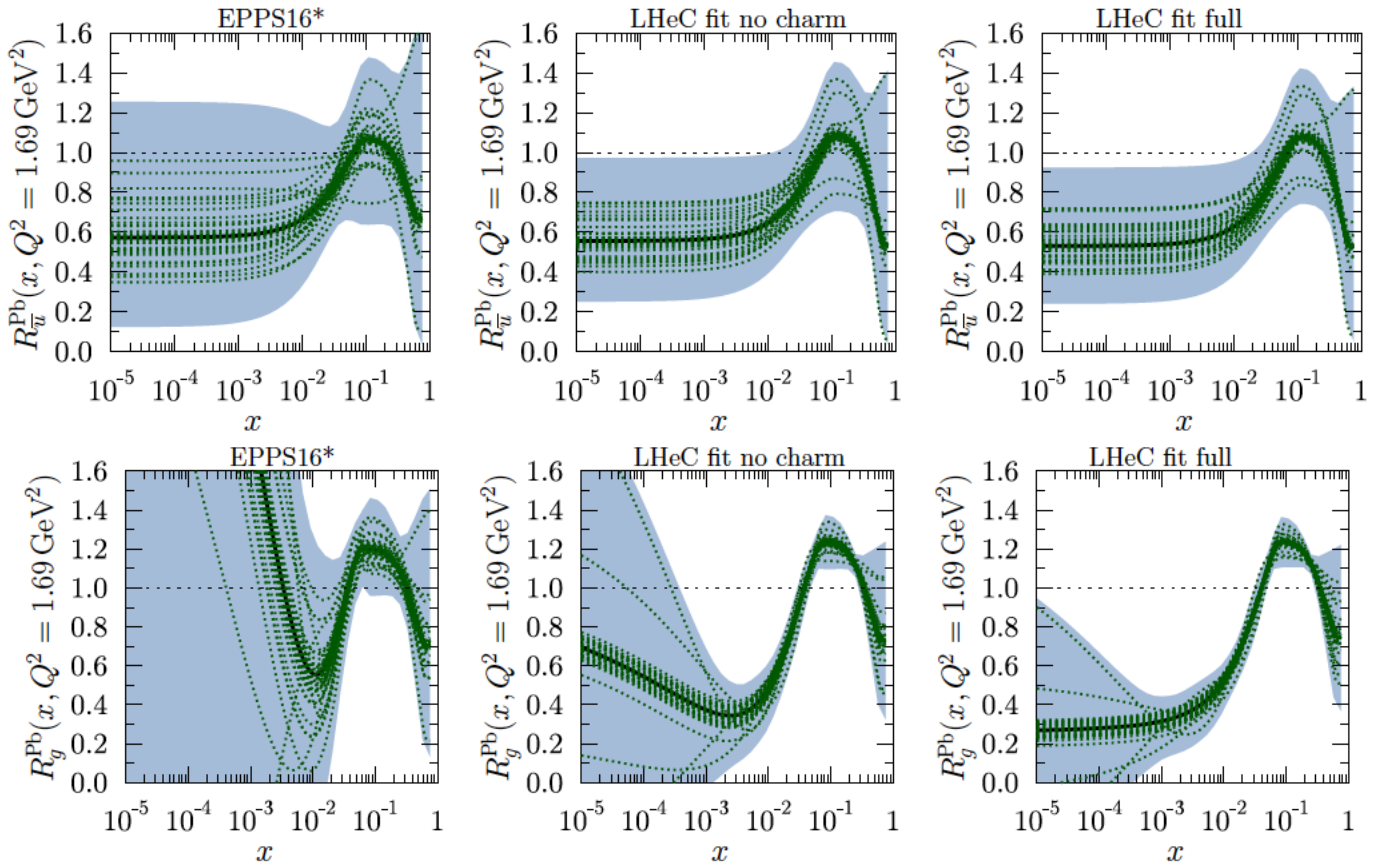
- LHeC/FCC-eh ePb pseudodata included in EPPS16-like global fits: large impact.

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

- Inclusion of charm has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.



LHeC



sea

glue

nPDFs: fits

- LHeC/FCC-eh ePb pseudodata included in EPPS16-like global fits: large impact.

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

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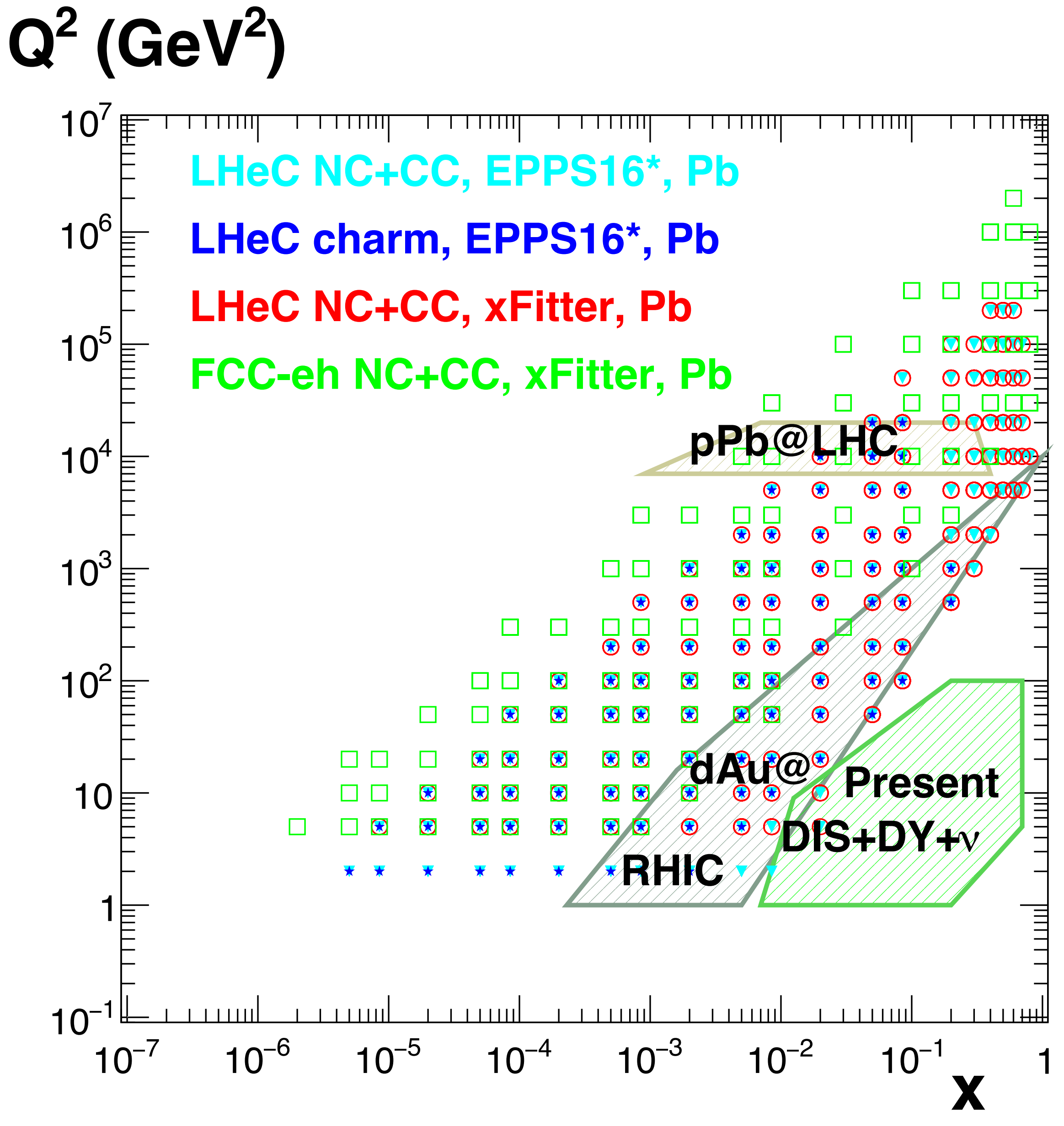
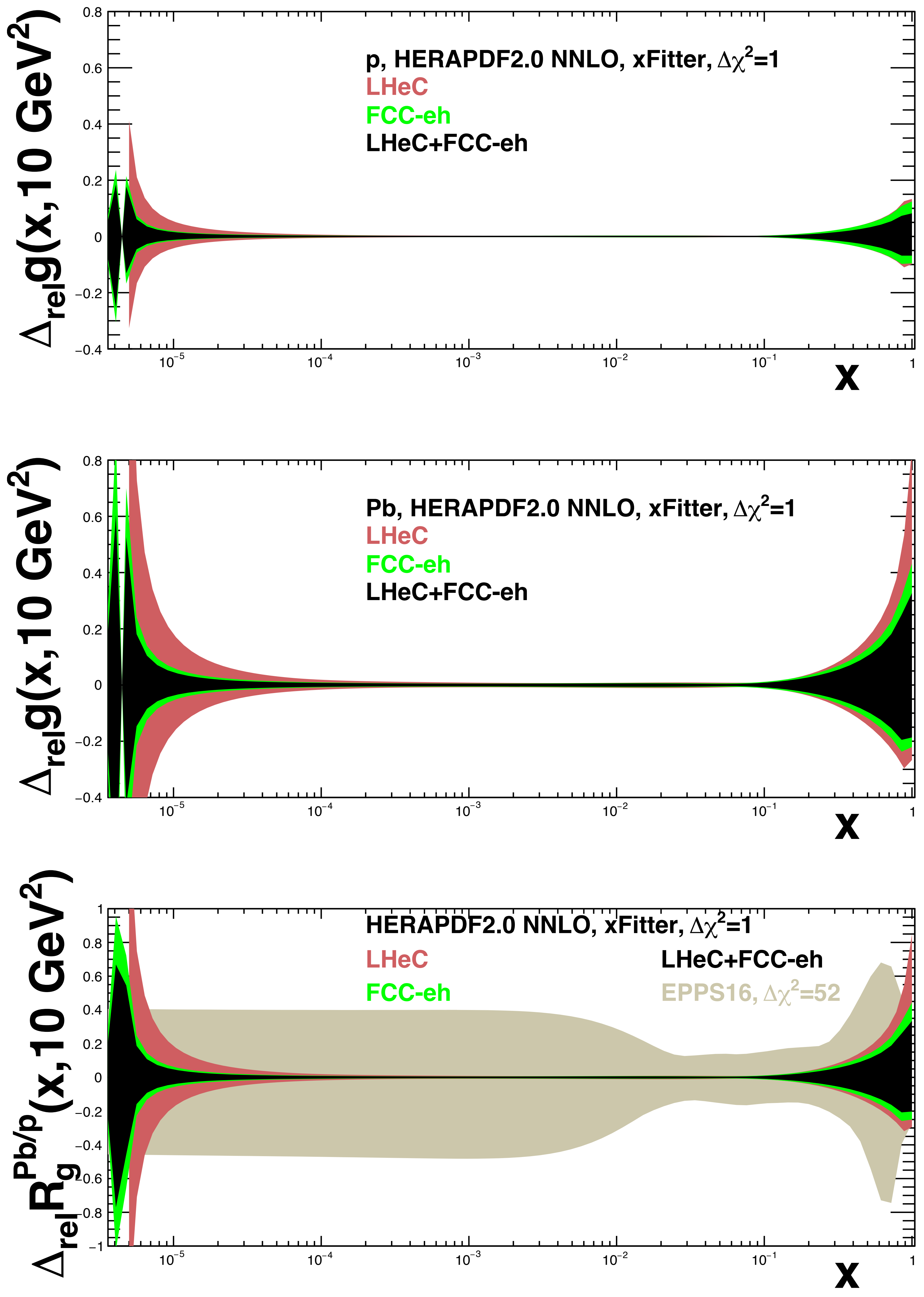
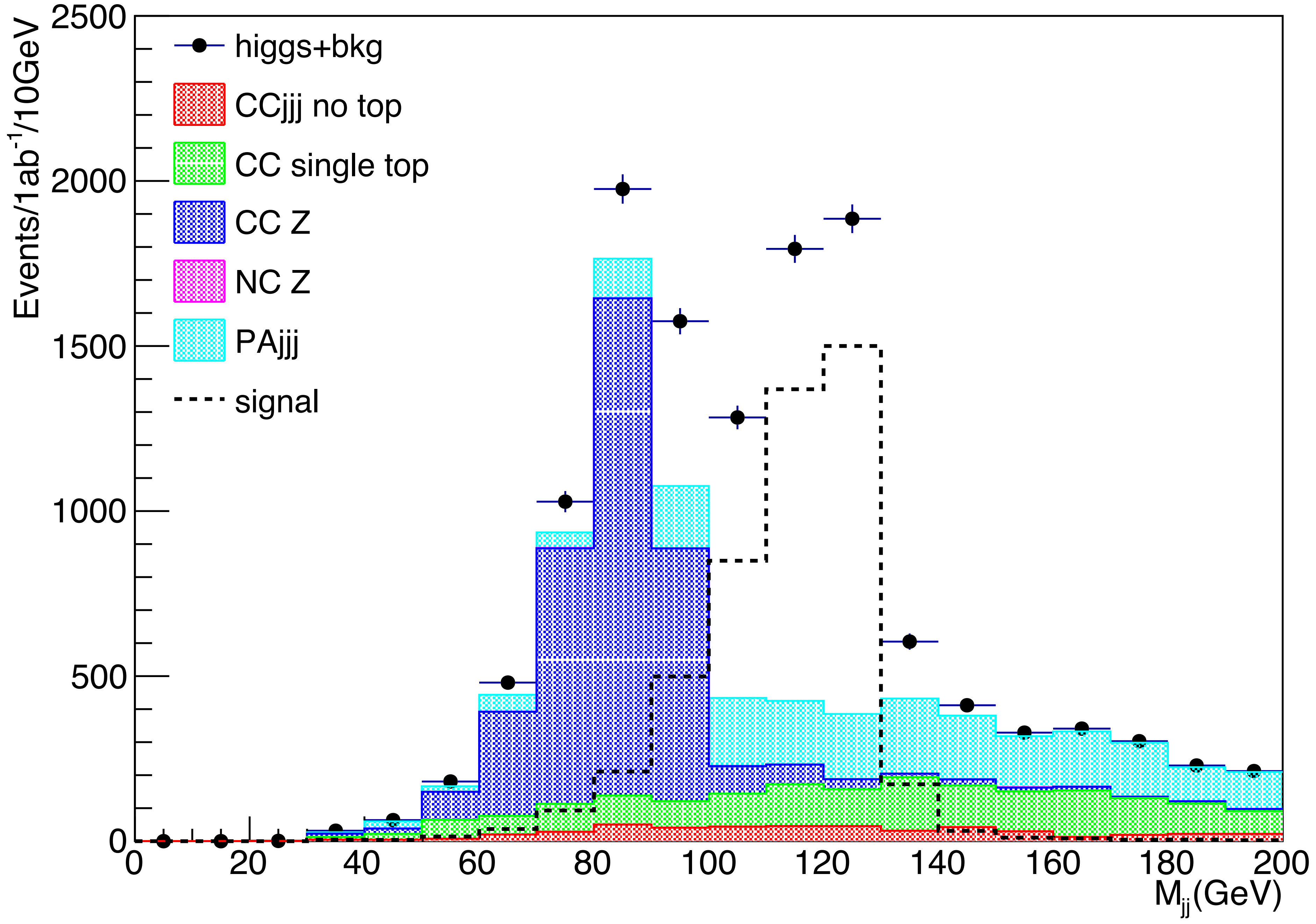


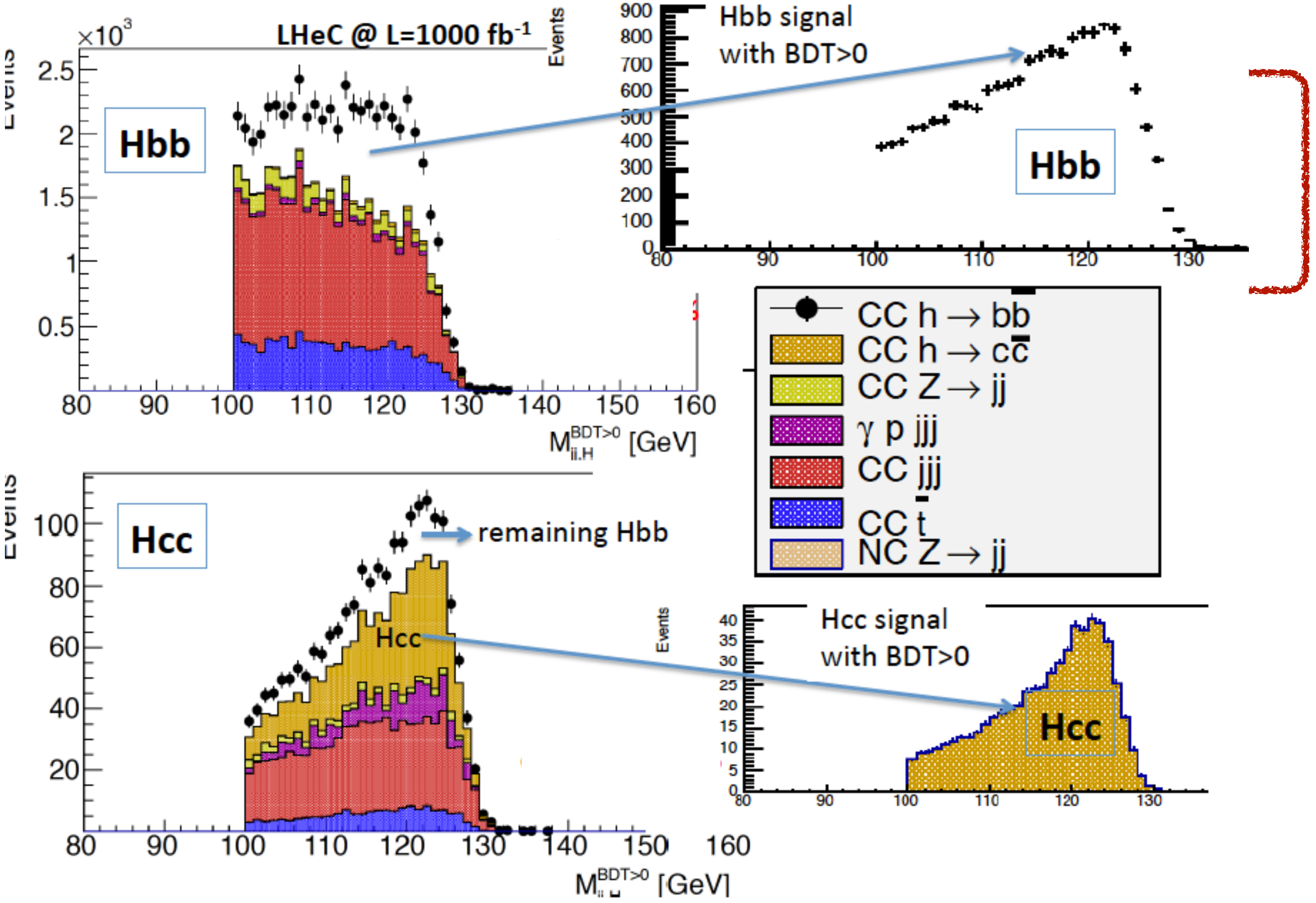
LHeC



Higgs in ep: signal strength

- Decays to bb and cc, P=-0.8, detector level analysis with HF tagger, efficiency 60-75 (10) % for b(c)-tagged jets.

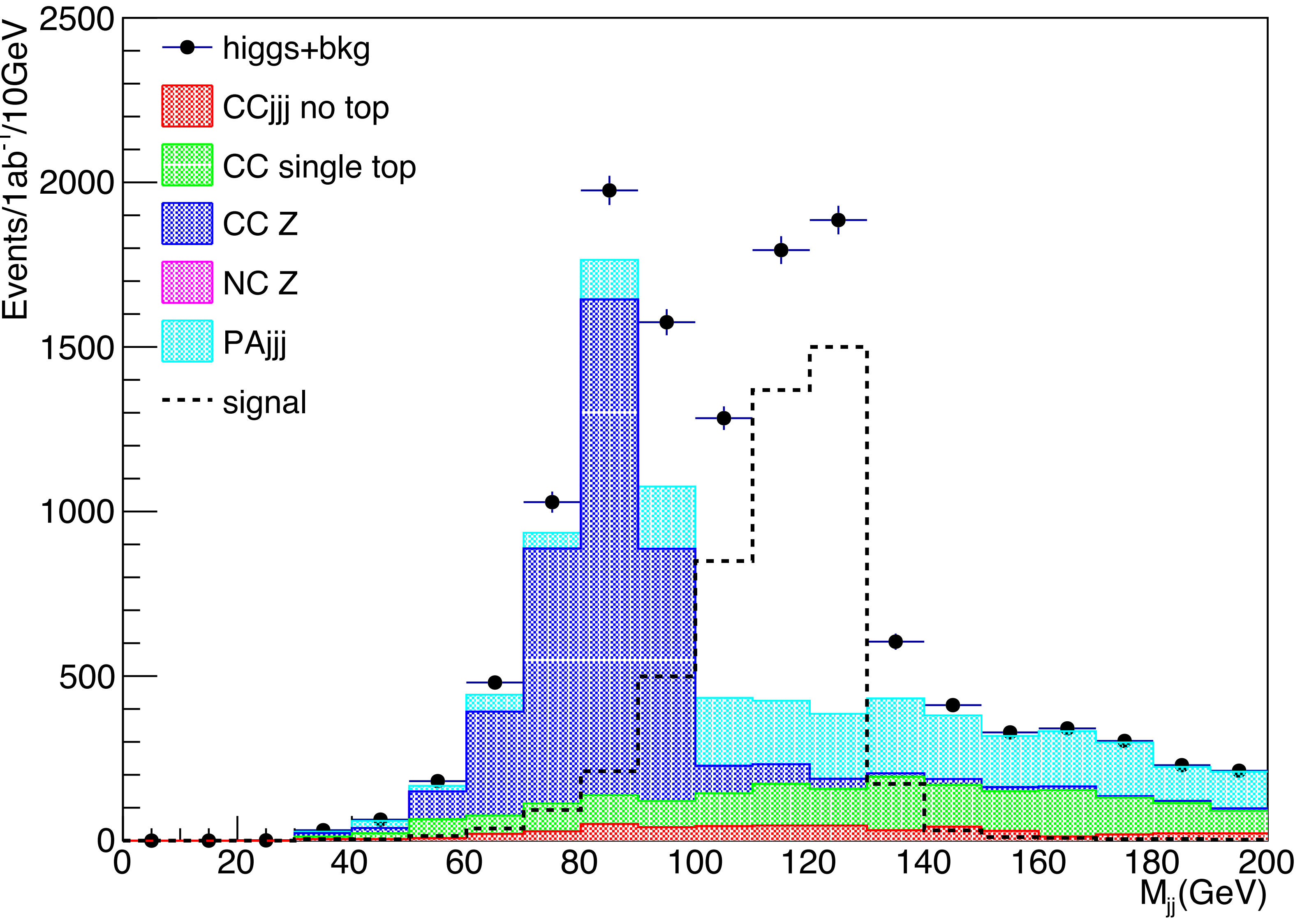


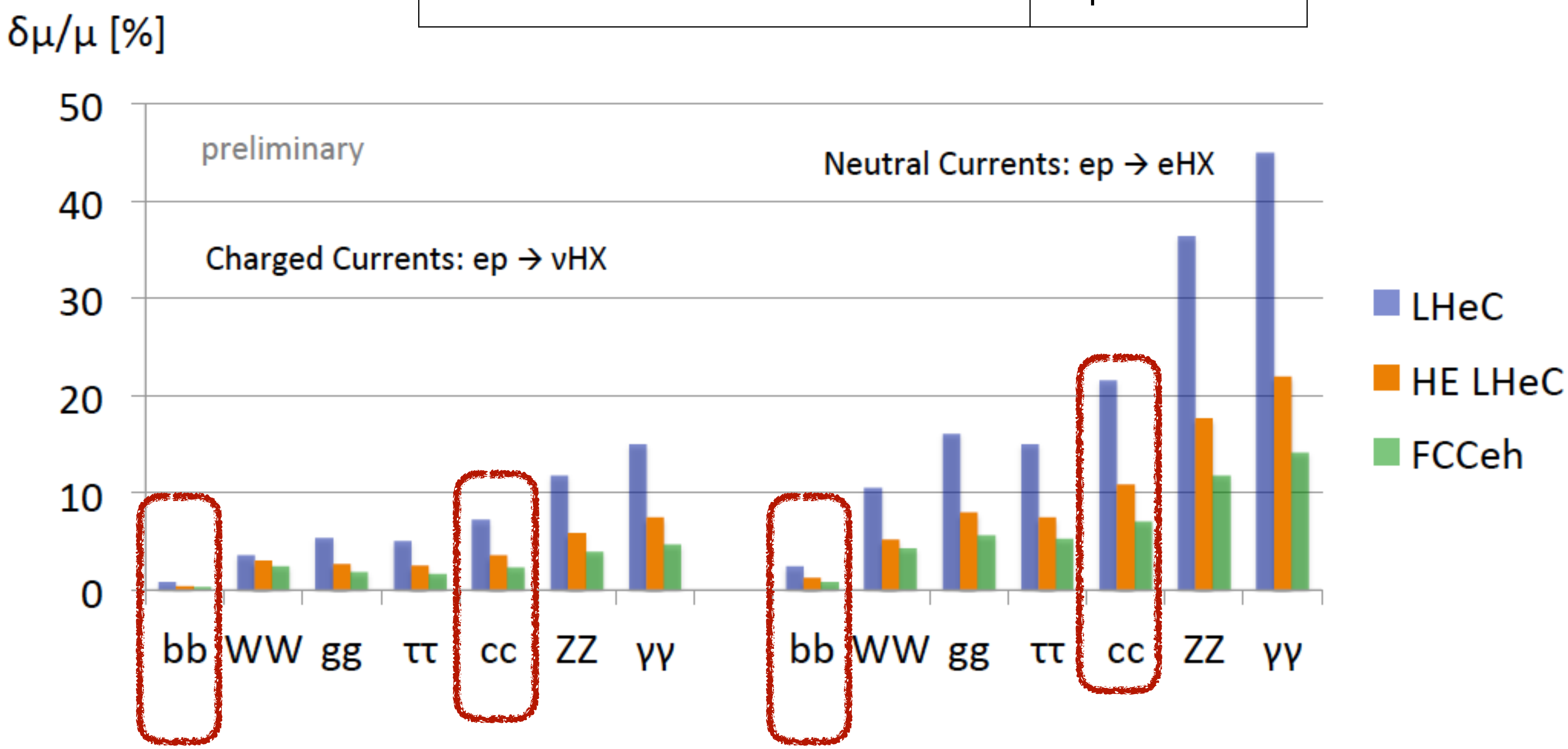


Higgs in ep: signal strength

- Decays to bb and cc, P=-0.8, detector level analysis with HF tagger, efficiency 60-75 (10) % for b(c)-tagged jets.

LHeC:	1 ab^{-1}	E_p=7 TeV
HE LHeC:	2 ab^{-1}	E_p=13 TeV
FCC-eh:	2 ab^{-1}	E_p=50 TeV



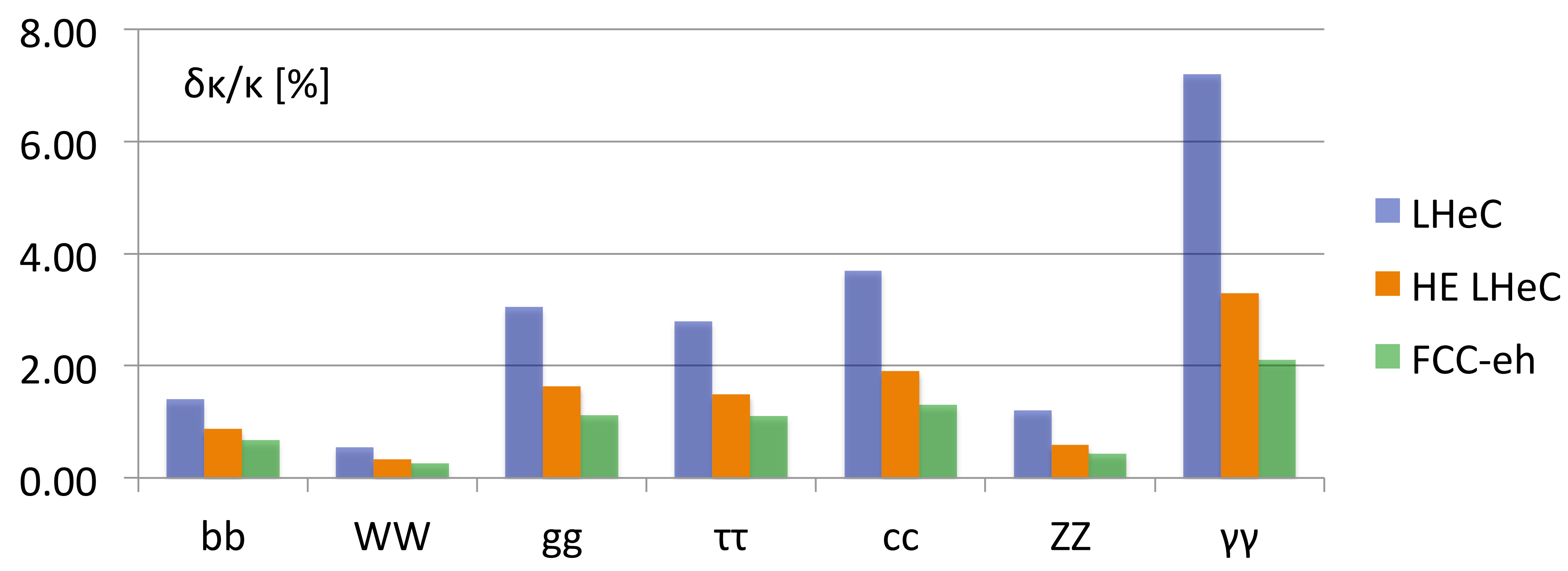


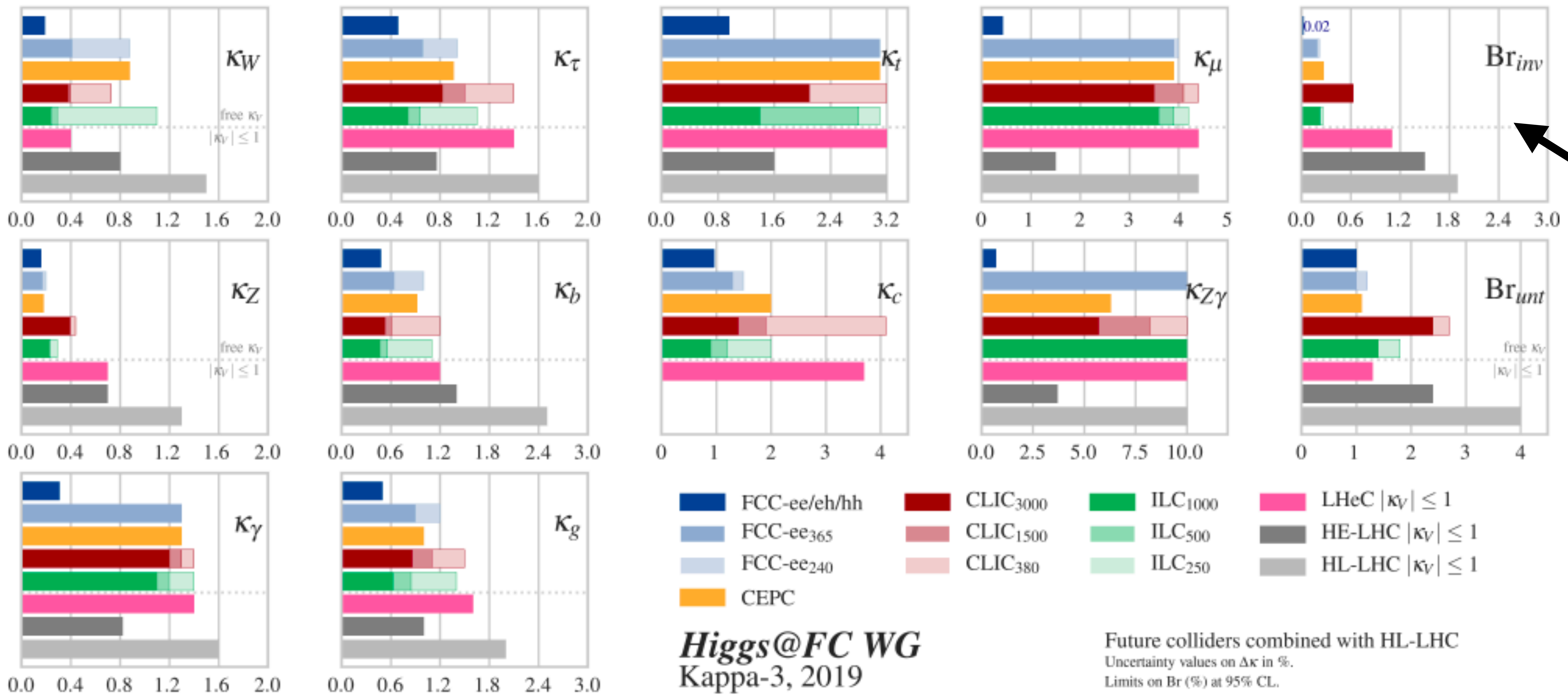
Higgs physics: κ framework

- κ_i : coupling strength modified parameters, powerful method to parameterise possible deviations from SM couplings.

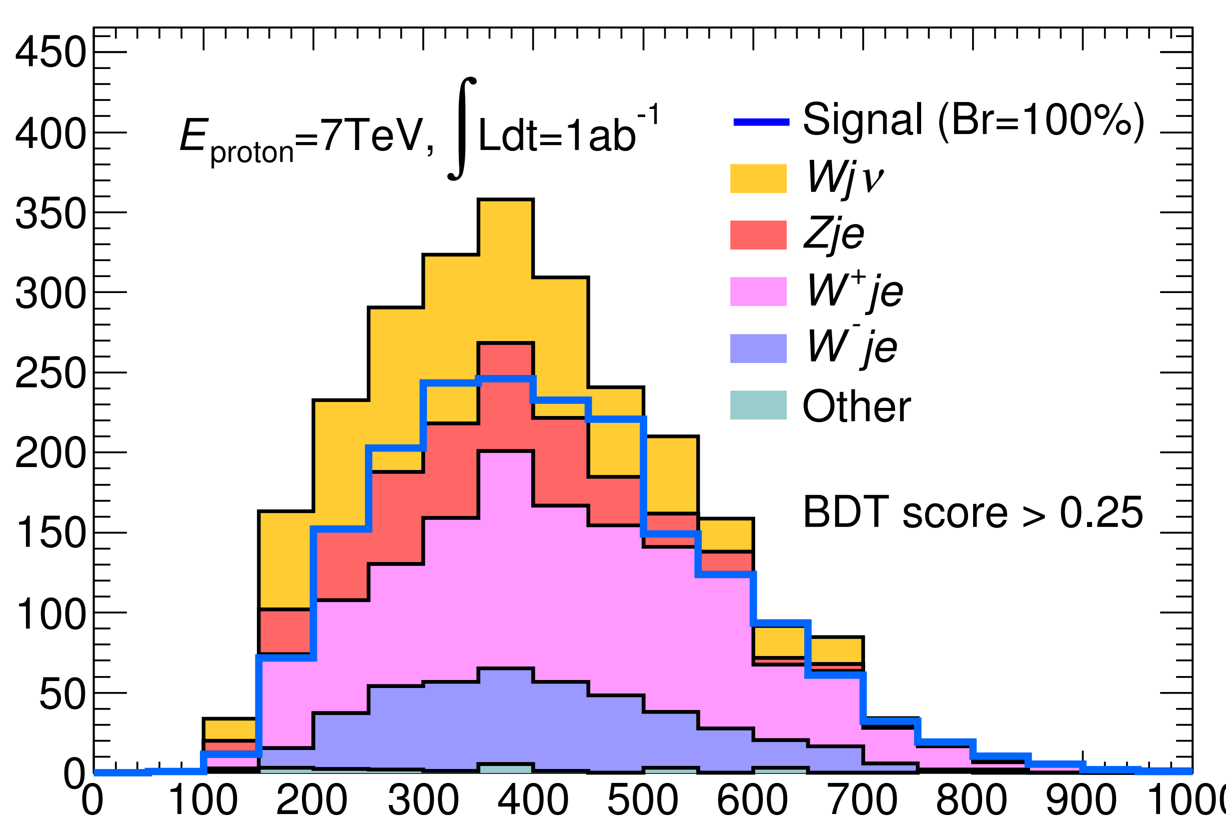
$$\sigma^i_{CC} = \sigma_{CC}\, br_i \cdot \kappa_W^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j}$$

$$\sigma^i_{NC} = \sigma_{NC}\, br_i \cdot \kappa_Z^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j}$$





Note: good potential for improving on **Higgs invisible** with HL+LHeC but more refined analyses needed



$\mathrm{Br}(h \to \text{invisible}) = 6\,\%$ at 2σ level